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March, 1950

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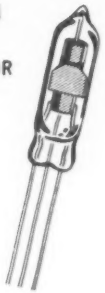

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NUCLEONICS

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The Atomic Industry and Human Ecology

VIII—NEVER POINT AN EMPTY GUN

REMEMBER THE ADAGE: *Never point a gun at a man unless it is loaded.* Better never to point a gun at all. But if a weapon is directed against man or nation, let it be loaded and aimed true. For the other fellow may not be pleased, and an empty gun, like a four flush in poker, cannot deliver if called.

Perhaps the analogy is poor. There *are* many miles between Washington and Moscow, but no more than the B-36 can fly; and the Voice of America, even as a "whisper," is sufficient for us to know that Russia knows what our President and other leaders have stated about the H-bomb. With Senator McMahon one must agree, "The President's decision was dictated by the severe realities of the world which we inhabit today. He had no choice, and his decision under present circumstances is right." The American people must quickly realize that *from the Russian point of view*, which is not without importance in these matters, an even more potent atomic weapon than the bomb by fission has been pointed straight at their vital organs. Now the United States must "put up or shut up."

Fortunately the weapon has so far only been pointed, not discharged—that is the new weapon; the "old weapon" was first used by the United States over Japan on August 6, 1945. Since that time we have shown quite a creditable hand with atomic energy, in a minor-league way respecting peacetime applications. We have devoted more energy and money to atomic weapons, as we are assured from time to time, "During the first half of 1949, development and production of weapons and fissionable materials continued to be the central concern of the national atomic energy program and of the Commission." Thus the AEC reported, as required by the Atomic Energy Act of 1946.

In the Seventh Semiannual Report of the AEC, we read: "Production of weapons was changed to an industrial type of operation. . . . The technical and scientific staffs were recruited more nearly to the desired levels both in quantity and quality. Industrial strength was added to the program by new contractors in various fields, but especially in weapons and reactors. . . . As of July, 1949, nearly 9,000 scientists and research engineers were at work on AEC research projects. . . . The new team contained fewer 'big names' of science and was composed largely of younger scientists and engineers."

Also during the period of the Seventh Report, the President announced an atomic explosion in the U.S.S.R. This event, followed by the discussion on H-bombs and the Fuchs case, precipitated much talk by many people along every conceivable line. There are some disagreements in these statements, but they are remarkably unanimous in the fundamentals: (1) "It's just terrible," and (2) "There's nothing I can do" (or "Where's the sports page,

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Honey?"). The rare individual shows some sign of tolerance, which is not necessarily good, and Einstein has pronounced correctly, "Solemn renunciation of violence (not only with respect to means of mass destruction) is undoubtedly necessary."

The general public seems unimpressed by the opinion, stated with varying degrees of forcefulness by Einstein and others, that "radioactive poisoning of the atmosphere and hence annihilation of any life on earth has been brought within range of technical possibilities." Is it possible that the average man would prefer annihilation among his contemporaries to a more selective torture? Does the average youth avoid nicotine because it can be used to annihilate insects? Will the average driver take the parkways at five miles per hour under or over the limit with no officer in sight—even though he knows thousands die every year in automobile accidents? Do you?

NUCLEONICS believes with heart and soul that the fear psychology of recent years is bad for the United States. Fear psychology may be good for the still obviously young and physically expanding nation in use against her neighbors. We have stated in these columns before that the atomic industry is essentially a young man's industry. We are delighted to read in the AEC reports that our "new team" consists largely of the young scientists and engineers. *Herein lies our strength.* For the atomic industry is a young industry into which six, twenty, yes a thousand and more times our present effort must be put. There is theoretically no limit to the power of an H-bomb, nor is there limit to the good that can come from man's control of atomic energy.

When, where, and by whom atomic energy will be brought under control in the full sense of the word remains to be seen. NUCLEONICS admits no reason why this cannot be accomplished on earth, rather than in some other galaxy than our own (we do not know this has not already been done). The goal to be won is great and the effort required to win it is also great; and there is no other alternative than control or annihilation.

We leave to others more skilled in these things the task of planning and blueprinting atomic control in its entirety. In view of what is true at present, however, three things are necessary:

I. Overclassification must stop. Penalties should be imposed for maintaining classification of documents or devices when they no longer contain information that is (presumably) still secret. As a practical measure, each classified document or device may have its grade of classification reduced at intervals of six months, say, unless there is proof that classification must be retained (or even raised) for reasons of military, *not bureaucratic*, security.

II. The particles of modern industry—alphas, betas, gammas, neutrons, and X-rays—must become as widely known and used as cars, radios and television, sports, and aircraft. Through use in daily living, our children and we must learn to live with radiation and with all the instruments and devices of radiation.

III. The monopoly of the people—"atomic energy"—must be exercised by all the people. Atomic energy is not for the military alone. Atomic energy must not remain the business (essentially) of the AEC alone. Atomic energy must soon take its place throughout civilization wherever man discovers a need that it can satisfy.

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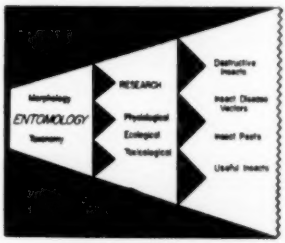
GENERAL ELECTRIC

Radioisotopes in Entomology

Nucleonics in entomology can be expected to help man combat insect enemies of agricultural and medical importance. Tagging mosquitoes to learn their flight range is an example of some of the research here reported to indicate the possibilities that radioisotopes hold for this science.

By DALE W. JENKINS and CHARLES C. HASSETT*
Medical Division, Army Chemical Center, Maryland

IN THE PERPETUAL BATTLE between insect pests and man, any new weapon is welcome. Radioisotopes offer an excellent tool for research on problems that in the past have been insoluble or difficult of attack by conventional methods. The use of these radioactive tracers has already yielded good results, and as biologists learn more about their possibilities and how to employ them, we may expect a constantly widened application of these tracers.



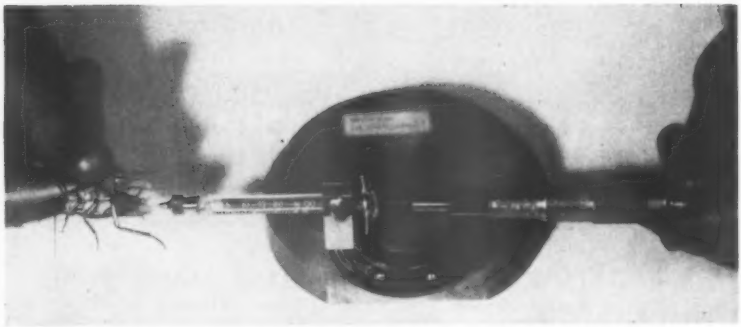
The importance of insects to the human race is difficult to state in dollars or in lost food and materials, but an estimate of the damage done to agricultural and forest crops and products in the United States is about 4 billion dollars per year (*36*). In the world generally, insect damage is vastly greater and the total economic importance of insects is staggering. Disease-carrying insects have killed millions of people, while other millions are reduced to a marginal existence by diseases such as malaria, yellow fever, and sleeping sickness.

On the other hand certain insects are beneficial since they supply silk, honey, beeswax, shellac, *etc.*, valued at about one-half billion dollars annually. The yearly value of insect-pollinated fruits, vegetables, and flowers is estimated (*27*) at over 2 billion dollars for the U. S. alone. Insects also serve as food for fish, birds, and other animals, and many insects are important either as predators or parasites of harmful insects.

In surveying the field of entomology, one can, for convenience, divide it into several parts. Classical taxonomy and morphology flowered into physiological, ecological, and toxicological research. This research has affected and will continue to affect the areas where insects come into personal or economic contact with man. The problems that arise from these contacts can be solved only by intensive and coordinated research which must be planned at all levels.

It is not enough to learn more about the use of insecticides, but more must be learned about the insects as well, for it is by no means certain that we

* EDITOR'S NOTE: Dr. Jenkins is an insect and plant ecologist specializing in the ecology of medically important insects and arctic mosquitoes. Dr. Hassett is a physiologist specializing in dietary needs of insects and carbohydrate metabolism.



Microinjection of gamma-emitting radiozirconium (Zr^{95}) into abdomen of an anesthetized cockroach (shielding removed for picture)

have the upper hand. If this has not been clear in the past, it has been made so by recent developments in the use of DDT. The one-time wonder chemical, which was to have permanently conquered most of our insect enemies, becomes less useful year by year as more insects acquire a resistance for it (*4, 22*).

The problems thus posed can only be solved by thorough understanding of the basic physiology, genetics, and ecology of insects, plus a knowledge of their reactions to various toxic materials.

Use of Radioisotopes

The rapidly increasing number of papers describing the wide variety and use of radioelements now offered scientists attests their value in research. Yet the biologist who has no special training or facilities for work with radioisotopes is likely to question the feasibility of applying them to the solution of his problems. Are the techniques too cumbersome, the apparatus too expensive, and the hazards too great? The answer is "no." Here briefly are the factors to be considered:

Equipment. The usual radioisotope laboratory equipment is needed. A monitoring instrument should be available to prevent unnecessary exposure and to detect contamination of clothing, laboratory benches, *etc.* This may be of the laboratory line-operated type, or a more portable battery-operated one. The latter is to be preferred if operations are to be extended from the laboratory to the field. The usual precautions for low-level radiation procedures should be followed. Publications available from both the Atomic Energy Commission and the National Bureau of Standards are useful guides to the necessary equipment and safety precautions.

For quantitative measurements in the laboratory, a scaler is needed to render precise data in terms of disintegrations per minute. This type of equipment gives a measure of over-all activity of the material. For studying the distribution of elements in whole mounts or sections of organisms, radioautographs can be made by exposing X-ray or other suitable film to the specimens.

Selection of isotopes. For biological work, radioisotopes are used to follow events in time, or materials in space, frequently both. For example, one may follow the rate of accumulation of an element and its final distribution in insects; one may also follow the distribution of insects from a breeding site.

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The first problem demands a specific element; the second might be handled as well with any one of several. Where a choice is possible, the best combination of characteristics should be sought, considering such points as the following:

1. *Biological importance of the element.* The elements which are predominant in protoplasm will, in general, receive the most attention. A few, for example hydrogen, offer no readily useful radioisotopes. Some offer several isotopes with differing properties, but it will be noted that chemically all behave alike. Biologically, not all elements function alike and one must consider this as a possible limiting factor. Thus, the rate of turnover of one element is not the same as that of another. Sodium and potassium tend to move in and out of tissues rapidly. They are also taken up in greater quantities than such elements as barium or polonium. The common metabolites are readily absorbed by organisms from food or water. Other substances may have to be introduced by other routes if significant quantities are to be used.

Tissues also vary in their behavior toward substances. It has already been shown that iodine is accumulated largely in the insect exoskeleton, and barium, which accumulates heavily in the gut, Malpighian tubules, and fat body, is not found in the nervous system.

2. *Half-life.* The rate of radioactive decay of a particular isotope, measured in terms of its "half-life," may determine whether it is a suitable one to use. A half-life may be only seconds or minutes, or it may be months or years.

3. *Type of emission.* Neutron- and alpha-emitting isotopes would be desirable only under very special circumstances. The physiologically important substances are beta and gamma emitters. Beta emitters are to be preferred for most work because the radiation is much less penetrating. This greatly reduces the necessity of shielding. As a corollary to this, it should be noted that some beta emitters decay in two stages, the second involving the emission of a gamma ray.

4. *Availability.* While dozens of radioisotopes are theoretically available, only those which are pile-produced are now made in quantities. Cyclotron products cannot be made in large amounts, usually require much refining, and are thus generally more costly and less readily obtainable than the others.

Radioisotopes are available from the AEC for approved projects. Many labeled compounds of various kinds are now available from the AEC or commercial suppliers, and special non-stock chemicals can frequently be had from these sources if the investigator is not equipped to synthesize materials himself.

Ecological Research

In nearly all methods of control of insects, ecological information is required. Ecology is a broad science which studies the relationships among organisms, and between organisms and their environment. It also includes the study of life histories, behavior, and dispersal.

Insects occur in large numbers in the air, soil, water, and inside and outside of plants and animals. Their study is often made difficult either because they are small in size, because they remain buried in soil, plants, or in animal bodies, or because they may be nocturnal. It is manifestly difficult to trace their movements under these conditions. Yet life cycles must be worked out, and ways in which insects affect and are affected by other organisms must be known if we are to find effective means of controlling harmful insects.

Suitable methods of marking individual insects have been greatly needed for a long time. Until recently it was

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Radioactive arctic mosquitoes emerging from the surface of a breeding pool in Hudson Bay

done by applying brightly colored or fluorescent dyes, metallic dusts, or other visible marking agents. These methods were frequently injurious to the insects and were time-consuming since they usually involved individual examinations. Now insects can be tagged dependably with radioisotopes and can be detected with ease even through soil or the bodies of host animals.

In attempting to control the spread or depredations of harmful insects, the rapidity of movement and distances traveled are of importance. It is often necessary to establish quarantine zones, as for the Japanese beetle, gypsy moth, European corn borer, and many other insects of enormous destructive potential. During World War II, malaria was a continual menace to our troops, and the flight range of the *Anopheles* mosquitoes frequently influenced the location of military bases and determined methods of control. These problems are now being attacked by investigators using radioactive tracers.

Radioactive yellow fever mosquitoes *Aedes aegypti* were produced by Hassett and Jenkins (*17*) using P^{32} in the larval-rearing medium. At Lagos, Nigeria, this species was marked by Bugher and Taylor (*7*) using P^{32} and Sr^{89}, and it was found possible to recover marked mosquitoes, 3,800 feet from the release point. Arctic pest mosquitoes *Aedes pullatus* and *Aedes excrucians* were made radioactive by Jenkins (*21*) at Hudson Bay using P^{32} in open pools.

In the vast expanses of the American arctic, mosquitoes breed in huge numbers. They are severe pests throughout the summer and their dispersal is apparently great. Recently the Alaska Insect Control Project airplane sprayed 100 sq mi with DDT and killed the mosquitoes there, but reinfestation by other mosquitoes occurred in the area in about one week. The range of mosquito dispersal is now being studied by means of radioisotope marking.

Malaria, house, and rockpool mosquitoes, houseflies, fruitflies, and screwworm flies were made radioactive (*18*) by mixing P^{32} with the food of the larvae. Cockroaches and flesh flies were injected with gamma-emitting Zr^{95} to study the possibility of locating insects at greater distances than with beta-emitting P^{32}.

The underground movement and dispersal of earth inhabiting insects has been studied with radioisotopes. Tomes and Brian (*39*) placed a small amount of Ra^{226} under the wings of wireworm beetles, and Arnason *et al.* (*3*) inserted a small Co^{60} wire in the body cavity of wireworm larvae. The depth, location, and lateral movement underground were traced. Tracing the underground movements of plant-destroying insects and the paths of livestock parasites through the animal body suggests new methods of control that could be applied to these agricultural pests.

Food relations. Radioisotopes provide an excellent method of determining the food relationships between organisms. Certain insects live on other insects, on plants, or animals, but some-

times it is unknown whether these insects are parasitic, help, or have no effect on the host organism. If it can be shown that one organism derives food from the other, the parasitic status is proved. This has been done for a suspected mite parasite of the cockroach by Cunliffe (*12*). P^{32} introduced into the roaches was detected later in the mites.

Female yellow-fever mosquitoes became very radioactive (*18*) after taking blood meals from rabbits and white rats which had been injected with P^{32}. Mosquitoes have been observed to rest or probe in stems and flowers of plants but the actual feeding was often a matter of speculation. Now it has been shown that both male and female yellow-fever and house mosquitoes became radioactive when feeding on the juices of stems and flowers made radioactive by having the stem tips inserted in P^{32} (*18*).

Disease transmission. Radioisotopes are proving useful in demonstrating the method of transmission of plant diseases by insect vectors. Po^{212} was used by Hamilton (*15*) as a tracer to show the quantity of material removed from a plant by a feeding aphid and also the amount of ingested material that was returned to the plant during the next feeding period. The two-spotted spider mite *Tetranychus bimaculatus* and its eggs became radioactive when Rodriguez (*35*) reared the mite on bean plants grown in P^{32}.

The potato psyllid *Paratrioza cockerelli* is an important sucking insect which transmits the "psyllid yellows" disease. The psyllid nymphs and adults became radioactive after feeding on plants containing P^{32} but normal plants did not become radioactive from being fed on by the radioactive psyllids, according to Pletsch (*33*).

The pineapple mealybug *Pseudococcus brevipes* transmits striping, spotting, and wilt disease of pineapple. Mealybugs fed on agar gel containing P^{32} became radioactive and transferred P^{32} to plain agar gels and to plants by their oral secretions [Carter (*10*)].

Measuring radioactivity of an arctic pool containing mosquito larvae and radiophosphorus

Radioisotopes promise to be useful tools in studying the malaria protozoan life history, especially the development of oöcysts in the mosquito, and the path of sporozoites in the body of the host after being bitten by the mosquito, and in adding information on the site of exoerythrocytic development on red blood cells in the host.

Predation. Many of our most injurious insects are kept in partial check by larger predacious insects. Field observations on predation are not numerous and radioisotopes can contribute much in this field. Radioactive mosquito larvae at Hudson Bay, Canada, were observed by Jenkins (*21*) to be preyed upon in the water in large numbers by dytiscid beetles and chaoborine fly larvae which then became very radioactive. In our laboratory, P^{32}-marked yellow-fever mosquitoes and fruitflies were caught and eaten by praying mantids which became very radioactive (*18*).

Food chains involving algae, plankton, aquatic insects, fish, birds, bats,

and crabs were studied by workers from the University of Washington at Bikini after the explosion of the atomic bomb (*1*). Food chains and food relationships involving insects were studied in a fresh-water bog lake in Nova Scotia by Coffin *et al.* (*11*).

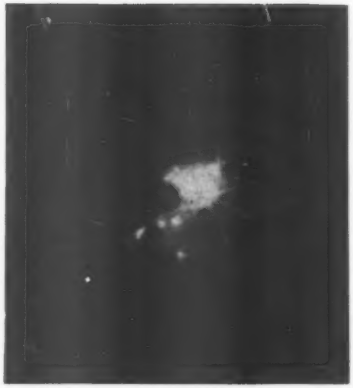
Trace elements, etc. Recent discoveries have shown that minute quantities of certain trace elements such as Cu, Co, Bo, Mn, Zn, Va, and others have great influence on plants and animals. In certain organisms, traces of some of these elements are essential for growth or reproduction; on the other hand, the presence of traces of some elements inhibits growth.

One of the most interesting finds is that plant resistance to insect attack sometimes depends on the amount of a trace element present. Progress in this field has been necessarily slow because of the difficulties of analyzing the minute quantities of trace elements involved, but radioisotope-tracing offers exceptionally good methods for microanalysis. Expected results will provide means of adjusting available materials in the soil to increase production of agricultural products and of developing or increasing resistance to insect attack.

Another insect-plant relationship that has not yet been investigated by the new methods, and about which all too little is known, is the pollination of various species of plants. When it is recollected that we are disseminating vast quantities of potent insecticides to stamp out destructive insects, and that the same poisons may act on those which pollinate many crops, the need for more exact information about these relationships is plain.

Effects of Radiation on Organisms

One of the most significant experiments of this century linked insects with radiation when Muller (*29*) showed that genetic changes were produced in fruitflies by X-rays. A generation of



Radioautograph of a radioactive yellow-fever mosquito

geneticists has explored this field using insects as the favorite subjects. This topic lies beyond the scope of the present paper, but it should be noted that recently radioisotopes have been substituted for X-rays in producing mutations. Enzman and Haskins (*13*) produced mutations in fruitflies with particles (neutrons) and Arnason *et al.* (*2*) with beta particles. It should be recognized that other manifestations of radiations may have gene mutations as fundamental causes.

Growth. Cell division, growth, and metamorphosis in insects is retarded or inhibited by high intensities of beta and gamma radiation. Gamma radiation of 128 roentgens retarded mitosis and cell division in the embryo of the grasshopper according to Carlson *et al.* (*9*).

Beta radiation from P^{32} retarded the growth and development of larvae (particularly earlier stages) of the yellow-fever mosquito when grown in concentrations over 0.3 microcurie per milliliter. The time required between larval molts, pupation, and adult emergence was proportionally greater at higher concentrations of P^{32} (*18*).

Beta radiation from P^{32} of 1.3×10^6 counts per minute per milliliter of the

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medium affected the growth, pupation, and adult emergence of fruitflies according to Arnason *et al.* (*2*). Pirrung and Hassett (*32*) showed that this is accompanied by interference with the synthesis of desoxyribonucleic acid, but the precise site of action is still in doubt.

Retardation of growth and development by beta and gamma radiation has been observed in the development of various other insect species. Apparently X-rays have the same inhibiting effect since retardation was observed in larval and pupal development of *Culex* mosquitoes and calliphorid flies by Halberstaedter *et al.* (*14*), and in fruitflies by Mavor (*26*).

Stoklasa (*37*) and others have claimed that gamma radiation on silkworm larvae resulted in increase in the size of cocoons. The increased size of insects subjected to radiation might result from the retardation of pupation and the increased length of larval development, rather than from any stimulating effect of the radiation.

Reproduction. Higher intensities of radiation reduce the reproductive potential of insects. Female yellow-fever mosquitoes did not develop ovaries or eggs when they contained about 0.2 microcurie of P^{32} according to Bugher and Taylor (*7*). Female wasps of *Habrobracon* showed reduced reproduction when exposed to 2 roentgens per hour of beta radiation, and at higher levels reproduction was inhibited (*25*).

Conversely, low-level beta or gamma radiation has been claimed to enhance reproduction. The two-spotted mite reared on bean plants containing P^{32} became radioactive and, after 3 generations, produced 5,886 mites, while a control on plants containing P^{31} (the stable isotope of phosphorus) produced 5,221 mites. The probability that such a result would be obtained by chance is less than 0.014 and the difference is, therefore, statistically significant according to Rodriguez (*35*); however, in other tests the results were variable. No detailed and exact tests have been carried out to prove that either growth or reproduction is definitely enhanced by low-level radiation in insects, but this problem deserves more attention.

It appears that there may be two opposed effects of radiation, and a continuation of research along these lines should aid in ascertaining the boundaries between beneficial and harmful effects on growth and reproduction.

Physiological Research

The information in hand concerning the present status of radiobiological research shows some promising lines of work developing in physiology and toxicology. This grows directly out of the near-revolutionary developments of the last ten years. Under the spur of war, insect control has been based more and more on new and varied synthetic organic chemicals instead of on inorganics and natural products. The resulting emphasis on chemical research on insecticides was paralleled by a steadily rising amount of fundamental research on the physiology of insects. The scene was set for rapid adoption of such an obviously useful tool as radiobiology.

Up to the present, physiological investigations utilizing radioactive materials as tracers have been made chiefly as logical developments of earlier studies concerning metabolism and the distribution of elements in the insect body. An early paper by Lindsay and Craig (*24*) showed the possibilities of following the distribution of an element from sectioned material by making radioautographs with P^{32}.

Wheeler (*40*) studied the distribution of I^{131} in *Drosophila gibberosa*, finding the major part of it in the skeletal parts of the flies.

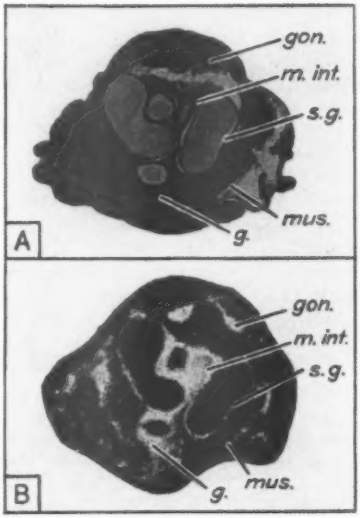
Bowen (*5*, *6*) recently made studies on the metabolism of certain metals in

hornets and wasps. Using Mn^{56}, he has demonstrated differences in the feeding of workers and the sexual forms of wasps. A complex metabolic cycle for barium (by the use of Ba^{140}) has been worked out and it has been found that hornets will accumulate barium when exposed to infinitesimal amounts. This suggested their use as detectors for radioactive leaks not otherwise detectable.* Ba^{140} decays to lanthanum which in turn goes to cerium. Such decay chains offer means of studying non-metabolites in organisms by the selection and introduction of the proper precursors.

Patton and Craig (*31*) have used labeled sodium chloride to study the permeability to sodium of the Malpighian tubules and other parts of the digestive tract of the mealworm.

Tahmisian (*38*) has demonstrated exchange of C^{14} between $C^{14}O_2$ in air and CO_2 in grasshopper eggs. Hassett and Summerson (*19*) found that similarly labeled carbon dioxide is taken up by adult *Drosophila* in the course of glycogen formation, and have thereby been able to extract C^{14}-labeled glycogen. Labeled protein has been produced by Zamecnik *et al.* (*41*) by injecting P^{32} into silkworms. Subsequent analysis of the proteins showed that the labeled carbon could be located on a carboxyl group of one of the amino acids.

These exploratory studies suggest at least two productive lines of research in the future. On the one hand, biosyntheses, using easily reared insects, may provide us with complex organic compounds labeled in various ways, which could be made *in vitro* only by long and difficult methods. On the other hand, isotopes can be used to elucidate the changes which go on in the insect body, and which are all too often complete blanks in our present knowledge. Now, for example, even such seemingly obvious problems as the discovery of the dietary needs and especially the foods of insects (often quite different from the materials actually taken in) are imperfectly worked out. There is, at present, a good deal of work being done toward chemically defined diets for various insects, and radioelements are certain to be valuable aids in it.



Radioautograph (B) and matching stained cross section (A) of the abdomen of a larval wax moth. White areas in (B) show tissues containing radiophosphorus.* (Abbreviations: gon., gonad; m. int., mid intestine; s.g., silk gland; mus., muscle; g., ganglion)

Three papers on inorganic insecticides have appeared. Campbell and Lukens (*8*) fed lead arsenates (Pb^{212}) to silkworms in a study of the permeability of

* It was reported in the AEC's Sixth Semiannual Report to Congress (Jan.–June, 1949) that biologists "will try placing hornets at key points near the new Brookhaven research reactor to test the possibility that the insects, by accumulating barium," a product of uranium fission, "will serve as indicators of radiobarium leaks long before they could be detected with instruments alone."

* E. Lindsay, R. Craig. *Ann. Entomological Soc. Amer.* **35**, 53 (1942)

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the gut wall. They found that the acid arsenate was more soluble and more of it penetrated the membranes than did the basic form. Norton and Hansberry (*30*) studied the toxicity of arsenates containing As^{74}. It was found that lead arsenate was more toxic to silkworms than arsenates of Na or Ca, even though less was absorbed. Morrison and Oliver (*28*) used $As_2^{76}O_3$ injected into the blood of mealworms *Tenebrio molitor* and dry $As_2^{76}O_3$ fed to tobacco hornworm larvae to study the toxic action and the distribution of the material. All this work attempts to trace the entry of the metal through the gut.

Penetration through the integument of the roach has been studied by Hansen, Hansen and Craig (*16*) by means of Br^{82} in a bromine analog of DDT. Another important study along this line has been contributed by Roan and Kearns (*34*) who labeled four organic phosphates, including tetraethyl pyrophosphate, and used them to study the absorption, distribution, and excretion processes following topical application.

Radioisotopes have been used in the study of two allied problems in the use of insecticides. Ladd *et al.* (*23*) found that radio-manganese, Mn^{52}, mixed into DDT sprays gave double the sensitivity of chemical methods of measuring the spray deposits, and they estimated that the use of more suitable isotopes, not then available, could increase it manifold. Hendricks (*20*) used C^{14}-labeled DDT in a study of the rate of deterioration of the compound in soil, a problem which had proved refractory when attacked with chemical techniques.

Goals for the Future

Ultimately, diverse lines of research are brought to focus on a practical approach to insect control. This means much more than the killing of insects. One of the most desirable goals in insecticide research is an increase in the selectivity of the compounds used, so that more and more harmful insects can be destroyed, while fewer beneficial insects are wiped out.

The second goal to be reached is a solution of the now-pressing problem of insects that become resistant to toxic materials.

Progress toward these goals can be accelerated by the coordinated efforts of ecologists, geneticists, physiologists, and chemists. In each of these fields, we have already seen radioisotopes being applied to research. It is clear that these new materials will influence profoundly all work to be done in the future and result in discoveries of great agricultural and medical value for the benefit of mankind.

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WE WOULD ALL AGREE that no scientist gives of his best in isolation. But in spite of everything we manage to do to foster the movement of scientists, and to effect personal contacts between them, we have to admit that they live chiefly on the printed word. After all, it is often by the medium of publication that a scientific worker may be helped—indeed inspired—by a fellow-worker whom he may never have seen and who lives thousands of miles away.

—*Sir Edward Appleton, F. R. S.*
"The Royal Society Scientific Information Conference Report"
(*The Royal Society, London, 1948*)

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Air Pollution and the Particle-Size Toxicity Problem—II*

Improved methods for characterizing air-born particulates are described in the interest of solving industry's air pollution problems, with emphasis on those chemically toxic materials used in atomic-energy production. Present-day demands prompt re-evaluation of older methods and careful consideration of instruments still in experimental stage.

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CURRENT industrial hygiene procedure is based on two axioms: (1) No substance is too harmless to be disregarded, and (2) no substance is too toxic to be used, if recognized as such, and adequate safeguards applied.†

If these axioms are granted, then it follows that methods must be available for detecting a wide range of types and sizes of dusts, fumes, mists and smokes (limiting the present discussion to air-borne particulates) and in all possible ranges of atmospheric concentration. This calls for extremely versatile instruments. Until 1940, most instruments could not fulfill such demands.

The first article of this series (NU, Dec. '49, p. 50) reviewed the type and diversity of the problems posed to industry and communities by air-borne particles with primary emphasis on those chemically toxic materials used in atomic-energy production.

This review, therefore, directs attention particularly to methods and instruments of recent origin that are especially suited to aid in the solution of these problems. Selected for inclusion are:

(1) the filter paper dust sampler and the electrostatic precipitator for quantitative estimation of particulate concentration
(2) the Modified Cascade Impactor and the oscillating thermal precipitator for characterization of particle-size distributions
(3) surface-coating techniques and the electron microscope as improved methods of resolution and measurement
(4) the Penetrometer and the Owl, indirect optical methods for characterization of particulates
(5) low-temperature ethane adsorption for the measurement of surface area.

These newer instruments surpass many of the older types by extending the size limits of detection and by offering increased sampling efficiency. Some supply information with the nicety required by current concepts of toxicologic action; most are practical instruments that should be standard equipment of the industrial hygiene laboratory.

Only brief mention will be be made of the many aerosol sampling and measuring instruments. These instruments have been described in detail, with data on comparative efficiencies, by Drinker and Hatch (*1*) and more recently by Patty (*2*). Much of the

* This paper is based on work performed under contract with the U. S. Atomic Energy Commission.

† Dr. James A. Sterner, Associate Medical Director, Eastman Kodak Co., Rochester, New York, 1948.

theoretical background for sampling and analyses of particulates is given by Dalla Valle (*3*). No descriptions of many of the newer sampling instruments have yet found their way into recent texts on industrial hygiene. The more demanding problems of today require the use of highly developed instruments.

In 1913, McCrae (*4*) first called attention to the importance of dust particle size. Industrial hygienists are now in agreement that a particle-size toxicity relationship holds but are not in agreement as to what limiting size is critical for the production of a toxic response.

For silica, Sayers and Jones (*5*) suggested a particle-size range of 1–3 μ. At that time (1938), the effects of smaller particles were not considered, largely because the available biological evidence stressed the significantly greater retention of the larger sizes. The lack of evidence for smaller particles closely paralleled the limits of available methods of sampling and, particularly, measurements with conventional microscopic systems. Later, with improvement in instrumentation, the toxic effects of particles below 1 μ have been stressed.

Hatch and Kindsvattar (*6*) extended the range in which silica shows increasing toxicity to include particulates below 0.5 μ and found that sizes as small as 0.18 μ acted with remarkable rapidity. Greater toxicity in animals has also been shown by the Rochester group for particles below 1 μ in diameter in the case of uranium dioxide (*7*). Recent findings of the causal role of particles of alumina abrasives of the order of 0.08 μ in Shaver's disease* and of the production of a diffuse pulmonary granulomatosis in rabbits by Vorwald (*8*), with particles of silica fume claimed to be 0.01 μ or less, extend the range still farther. Indeed, it now appears that pulmonary fibrosis may be the common response to particles 0.2 μ or below in diameter regardless of chemical differences.

To make real progress in such questions of critical particle size, improved methods of sampling and measurement must be in general use. Until recently no nonselective instrument was in general use for sampling air-borne particulates, nor were devices generally available for accurate measurement of dust below 0.5 μ.

The electrostatic precipitator came nearest to fulfilling requirements of nonselective sampling but, because of the manner of retaining the particles, it is more adaptable for concentration measurement than for counting and sizing. The Owens jet impinger, the konimeter, and the related Bausch & Lomb dust counter tend to be selective for certain size ranges depending upon their rate of operation. The Greenburg-Smith impinger, in addition to being relatively inefficient for small sizes under standard conditions of operation, has other limitations. The thermal precipitator is of relatively recent origin (1935); although widely used in England and Australia, it has not come into general use in the U. S.

Moreover, in addition to particle size, surface area is coming to be recognized as of equal if not greater basic importance in discovering causal relationships in toxicity. Many methods are now available for surface-area measurements of particulates. Although none of the precise methods are technically simple, that of inert gas absorption readily gives reproducible results and presents no unusual difficulties.

Selection of Instruments

The selection of air-sampling instruments for a given purpose is difficult for the following reasons: (1) New methods,

* Theodore Hatch, Director of Research, Industrial Hygiene Foundation, personal communication.

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or modifications of old, often have not been rigorously tested and confirmed. (2) Few developments of new instruments employed independent means of testing. (3) When comparative tests have been made, efficiency in measuring concentration as opposed to measuring size and number has been generally reported. (4) Moreover, even when comparative tests have indicated rational bases for choice, these choices have often been ignored. Witness the continued use of the Greenburg-Smith impinger in this country and the konimeter chiefly in Germany and South Africa, although critical evaluation of these instruments by Green (*9*) in comparison with the thermal precipitator showed it to be the best instrument. The fact that certain instruments have aided the solution of problems in the past is, alone, an insufficient reason for retaining them for the solution of the more demanding problems of the present.

Reference Methods

Basic to the development of new methods are reference methods whereby new procedures may be compared and standardized. Two reference methods will be mentioned,* the air-sedimentation cell, the special slit ultramicroscope. Both are based on sound theoretical considerations, although both have serious limitations with respect to lower size limits and practical applications.

The *air-sedimentation cell* (*10*) consists of a small closed cell in which a known volume of air is trapped and the suspended particulates are allowed to settle under gravity to a slide at the bottom. The settled particulates are subsequently viewed either optically or by the electron microscope. Lower size limits imposed by Stokes-Cunningham relationship vary with the density of the material; particles less than about 0.1 μ for materials of unit density are not detected. The upper limit includes all sizes and particles, even those of macroscopic dimensions. The lower concentration limit of air-dust is about 5 mg/m^3. Serious errors may be introduced by wall impingement and lack of thermal and electrical insulation. For particles below 1 μ, a prohibitively long period is required to obtain complete sedimentation; as long as three hours often is required for complete settlement of 0.1 μ particles. This length of time would be sufficient in many cases to change the characteristics of the particulates by aggregation at the air concentrations required for adequate sampling.

The special *slit microscope*, a modification of the Zsigmondy ultramicroscope, measures the rate of gravitational fall of a particle in air. The particle is illuminated by an intense source at right angles and observed through a horizontal microscope. Sizes are calculated from the Stokes-Cunningham relationship. The design most frequent used is some form of that developed by Whytlaw-Gray and Patterson (*11*). Numerous modifications have been made by various investigators to include studies of particulate behavior and charge. One of its chief disadvantages is the personal factor which tends toward subjective size-selection of the particles. The method is not a routine procedure.

The photographic modification of the slit ultramicroscope recently developed by Laskin (*12*), however, permits the simultaneous recording of a large number of particles in the form of tracks, the lengths of which are related to exposure time. This method, easily adaptable to routine measurement of large numbers of particles, offers a means for accurate counting of the smaller sizes which are resolved but do not settle under the influence of gravity. Since the ultramicroscope is useful for

* Other reference methods are described in (*1, 11*).

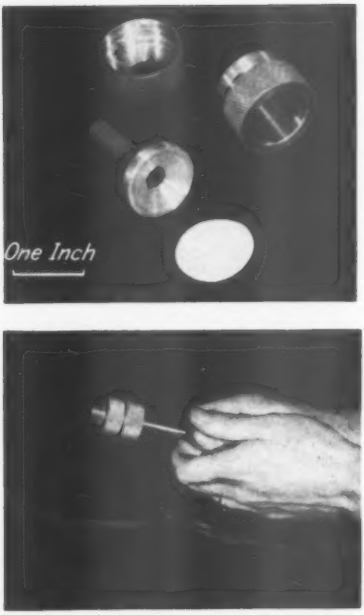

FIG. 1. Filter paper dust sampler.
Above: Parts of instrument
Below: Assembled instrument

measuring directly in the original environment of the particulates, special sampling devices are not needed. The limit of measurement depends upon density of the material and resolution of the system. Size ranges for materials of unit density have been measured from 0.2 to 10 μ diameter. For heavier materials such as uranium this can be extended to the submicroscopic range (0.01 μ).

Problem of "Nuisance" Dust

In industrial and laboratory atmospheres, the problem of distinguishing between toxic contaminant and normal "nuisance" dust is one of serious magnitude at low contaminant concentrations or at size ranges below 1 μ (where form and structure are less readily distinguishable). Relatively large quantities of nuisance dust (0.2 mg/m^3) occur normally in city atmospheres (*13*). Dust counts average 2×10^6 particles per cu ft with median particle size of 0.6 μ. Roughly 65% is carbonaceous material and 35% is ash. Nuisance dust of similar characteristics has proved a complicating factor in animal exposure studies at low dust concentrations (*14*); significant differences could not be found between dust counts of normal atmospheres and those of atmospheres to which the toxic agent has been added.

Nuisance dust has been one of the major factors preventing the adoption by industrial hygienists of devices capable of sampling smaller sizes. Later modifications of the konimeter and Owens jet counter have provided for the ashing of collected samples to facilitate removal of most of the nuisance dust in carbonaceous form. Unfortunately, until recently, no device provided for the identification of specific contaminants in a mixed atmosphere. The Cascade Impactor described below permits such distinctions to be made.

Air-Sampling for Particulate Concentration

The expression of dustiness in terms of concentration as opposed to counts per unit volume is fast becoming accepted because toxicity is more often related to the mass rather than to the number of particles per unit volume. This is certainly valid for soluble dusts, but for highly insoluble dusts such as silica it may be a less rational choice. Because counts are laborious and time-consuming, the use of "concentration" has a decided, practical advantage. Air samplers that furnish rapid and reliable estimates of concentration are valuable adjuncts to industrial hygiene practice.

Filter-paper dust sampler. Filtration as a means of separating dust from the atmosphere has been widely used in many forms. Coulier (*15*) originally

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showed that dust could be successfully retained by filtration through a layer of cotton wool. Filters have since been used of cloth, cotton wool, soluble chemical compounds, and paper of various types (*1, 16*). The more recent designs of the filter-paper dust sampler following the modification of Fairhall (*17*) have proved this method to be the simplest to operate and maintain for quantitative estimation of atmospheric dust concentration.

A filter-paper holder designed at Rochester for portability in field and laboratory use is shown in Fig. 1. External dimensions are $1\frac{3}{8} \times 4$ inches and construction, though conventionally of brass, may be of aluminum or plastic. The device consists of two removable pieces holding a $1\frac{3}{16}$ inch circle of filter paper exposing a sampling area 1 inch in diameter. Whatman #41 paper used at a sampling rate of 14 liters per minute has been found to be suitable for most laboratory and field problems. Samples that are nonreactive or nonhygroscopic can be rapidly assayed gravimetrically and may be verified by quantitative chemical analysis if desired.

For sampling, any convenient pump or vacuum source capable of drawing the required air volume is satisfactory. One that has demonstrated its merit in both our laboratory and field problems is a lightweight assembly fitted with a calibrated rotameter and designed to provide space for sampling instruments and other field equipment illustrated in Fig. 2. Other practical modifications of the sampling unit and field sampling pumps have been developed by W. Harris and personnel of the New York AEC Office. Critical features of the filter-paper sampler are the filtering efficiency of the paper and its relationship to rate of sampling, particle size, and atmospheric concentrations of the dust.

Studies at Rochester have indicated that with single sheets of Whatman #41 filter paper at a sampling rate of 14 liters per minute, the efficiency of the filter-paper sampler for many materials is better than 95% for a group of size ranges at atmospheric concentrations above 1–5 mg/m³. Comparison of the Midget Impinger with this instrument for collection of UF_4 dust (0.8 μ diameter at concentrations of 5–17 mg/m³) showed a relative efficiency of 73% for the impinger.

A more detailed study in terms of absolute efficiency based upon a quantitative estimation of the amount of sodium chloride aerosol passing the filter has been made by means of a flame photometer (*18*). These results, although preliminary, indicate that, for the particle-size range 0.1–1 μ (0.35 μ median), efficiencies of better than 90% were obtained with air concentration values above 13 mg/m³ and sampling velocities above 7.4 liters per

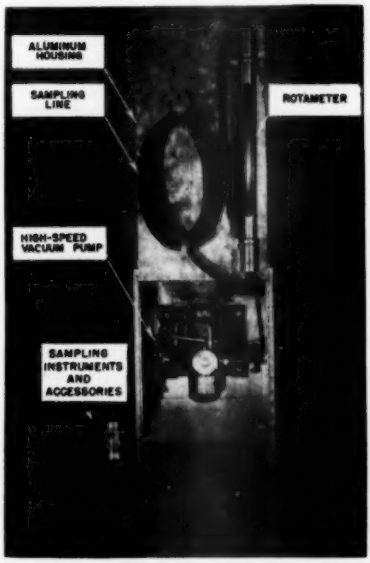

FIG. 2. High-speed vacuum pump in portable metal case shown open with drawer containing sampling instruments

minute. Increased efficiency was found with increasing sampling velocity and also with increasing air concentration. Thus, efficiencies of better than 97% have been obtained at a sampling velocity of 16.5 liters per minute at an air concentration of 59 mg/m³ and at a sampling velocity of 31.1 liters per minute at an air concentration of 13 mg/m³.

Increased efficiency was also found by increasing the number of filter papers used in the sampling head or in the form of a series train. The number varied with the concentration and velocity of sampling, but as many as eight papers were required to approach 100% efficiency as shown by the flame photometer.

Silverman (*19*) has also shown efficiencies ranging from 95–99% for cadmium and iron oxide fumes for a filter paper sampler using different papers.

Electrostatic precipitator. The particulates of a dust-laden atmosphere may be completely removed by passage between two charged surfaces of high potential difference. This has found application in numerous forms of instruments known as electrostatic precipitators (*20*). This well-known instrument is recommended as one of the best for collection of all types of particulates. It has high collection efficiency bordering on 100% over a wide particle-size range from fume dimensions up to 50 μ diameter if the rate of flow, voltage, and area of collection are adjusted to the physical character (density and state, *etc.*) of the particulate being sampled.

The limitations of this method are only those imposed by the compromise between cost and efficiency and are not inherent in the principle of the method. Moreover, inexpensive glass models may be constructed in the laboratory that are equally as efficient as more expensive commercial, portable models.

The electrostatic precipitator is best suited for the quantitative determination of concentration. However, it is not well suited for size-distribution analysis of most particulates because of size segregation along the collecting surface and because of aggregation of particles. The precipitator may not be used for the collection of easily oxidizable substances owing to the formation of ozone.

For example, the instrument will convert a portion of a collection of UF_4 to UO_2F_2. In such cases, the filter-paper dust sampler may serve satisfactorily. Under conditions which involve the simultaneous use of many precipitators in a limited space, the effluent air should be passed through activated carbon to remove the toxic ozone.

Particle-Size Analysis

General methods of characterizing particle size will be only briefly considered since detailed discussions may be found elsewhere (*1, 3*).

Most particulates possess irregular particle shapes for which no geometric diameter can be defined. A statistical diameter, however, can be rigidly defined. This is taken as the mean distance between the two extreme points on each particle when all particles, taken at random, are measured in one fixed direction (*i.e.*, horizontal axis). This gives a representative picture of the size distribution of the entire sample if the particles exhibit a chance distribution with respect to size and shape.

Most particulates encountered in industrial atmospheres exhibit a very wide range of size, generally presenting an asymmetrical or skewed probability of distribution of sizes. Normalization of the skewed distribution can be accomplished by expressing the sizes as logarithms, and then the distribution function can be numerically defined in

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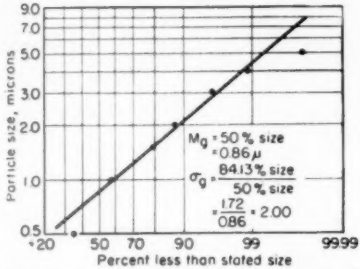

FIG. 3. Logarithmic probability plot of particle size distribution of a uranium dioxide sample

terms of the parameters of the corrected distribution. These parameters have been termed the geometric mean (M_g) and the geometric standard deviation (σ_g). Since the geometric mean is by definition an expression of that size at which half the particle population is either smaller or larger (50% size), the equivalent term *median* has been generally adopted.

To avoid lengthy calculations, a graphic method utilizing a logarithmic probability plot may be used. This involves a special grid based on a scale derived from the probability integral. The summation curve obtained by the integration of the logarithmic size-frequency curve is in the desirable form of a straight line, and the desired parameters are easily and directly obtained from the curve. The median (M_g) is the 50% intercept on the resultant curve, and the geometric standard deviation (σ_g) is obtained from the following relationship:

$$\sigma_g = \frac{84.13\%\text{ size}}{50\%\text{ size}} = \frac{50\%\text{ size}}{15.87\%\text{ size}}$$

Size-mass vs size-count medians. In the past, the characterization of particle size (expressed in micra) has referred to the average, or sometimes to the median, size value of the counted number of particles. Inasmuch as most toxicologic responses are more closely related to concentration of the toxic agent, the characterization of particle size in terms of relative numbers (counts) has little direct meaning.

A more useful form is the expression of the particle size in terms of the relative mass rather than number for the particle-size distribution. This function, termed the size-mass distribution, can be readily calculated from the size-number frequency data by the procedures reported elsewhere (*14*). Parameters of this distribution may be obtained similarly to those of the size-count distribution.

Figure 3 illustrates the graphic procedure for the particle-size analysis of a uranium dioxide sample in terms of the size-mass distribution. Although the theoretical probability function is a straight line, under practical conditions some divergence is usually found at the extremes.

Surface-coating techniques. The determination of small particle sizes by means of an optical microscope is not feasible unless special techniques are applied to meet both the maximal particle visibility and the resolution requirements.* This can be accomplished with the use of mounting media possessing refractive indices greater than 2, such as selenium or stibnite. Coating these materials over the collected particles by a vacuum evaporation technique has been described by Laskin (*14*). The apparatus required (*14, 21*) is essentially similar to that commonly used for the production of front-surface aluminum mirrors. This method is superior to the conventional technique of air-mounting and extends the practical resolution limits of the microscope from about 0.8 μ to approach the theoretical limit of 0.2 μ or less.

Figure 4 illustrates the striking effect of a selenium coating on a uranium

* These requirements are met by the electron microscope; however, in numerous cases where the instrument is not available or is not practical for large-scale, routine measurements, the surface-coating procedure is a valuable one.

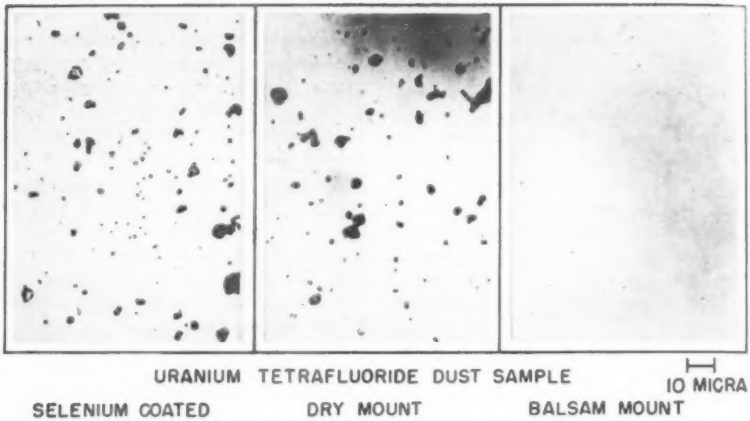

FIG. 4. Comparison of effect of selenium coating and conventional methods of optical viewing

tetrafluoride sample. With a common mounting medium such as Canada balsam, visibility is zero because the refractive indices of the particles and the medium are similar. In contrast with an air or dry mount (center) conventionally used to gain visibility, the selenium-coated sample shows increased numbers of fine particles, improved image contrast, and greater field depth. Glare and diffraction effects, tending to produce blurred images, are largely eliminated. The resolution of the microscope is increased to such an extent that the only limiting factors are those of the objective and condenser apertures and the refractive index of the immersion oil required for the optics.

The value of the coating procedure is illustrated in Fig. 5. Particle-size measurements were first made on a series of UF_4 dust samples using conventional methods. These samples were then coated with selenium, and approximately the same areas on each sample were remeasured. A progressive shift toward smaller sizes was found for each distribution. The sample shows a shift of 72% in median sizes between the coated and uncoated samples with values of 0.25 μ vs 0.89 μ, respectively. Although the extended range of the distribution for the coated sample is shown by the geometric standard deviation of 2.8 as compared with 1.7 obtained for the uncoated specimen, the modal tendency is stronger in the coated sample. These results have

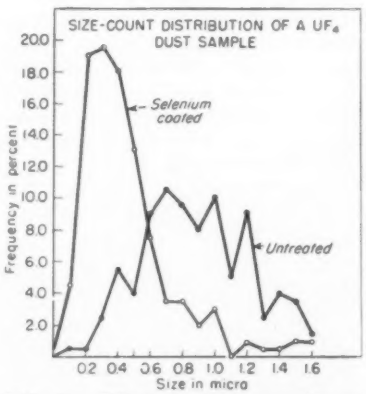

FIG. 5.* Effect of selenium coating on particle-size measurement

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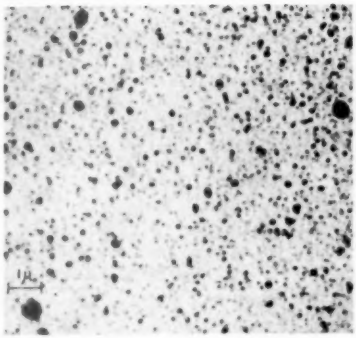
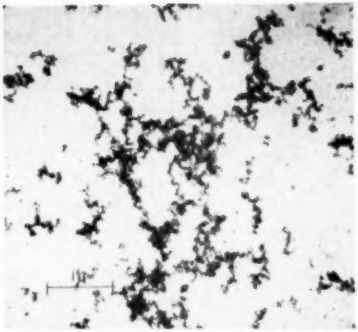


*Nonmetal fume, uranyl fluoride—shows no tendency to chain formation**



Metal fume, uranium dioxide—shows characteristic chain formation

FIG. 6. Fume types collected on electron microscope screen by thermal precipitator

been confirmed with comparative electron miscroscope studies.

Electron microscope. This instrument, indispensable for characterizing and measuring particles below one micron in diameter, is so well known that we need mention here only its specific applications to the field of small particles (*22*). Its general value lies in revealing shape and structural characteristics of the ultrafine particles below the size range of the optical microscope. The ultimate limit of resolution of the electron microscope is from 0.003–0.01 μ.

Shadow-casting, a technique similar to surface-coating, may be employed to increase resolution and to reveal another dimension (depth) of particles. Differential densities may also be revealed by the depth of shadows cast by the electron beam. In specific cases, it may be used to show contrasting characteristics of particulates of fume sizes.

Figure 6 shows two pictures of fumes taken by the electron microscope. The uranyl fluoride (UO_2F_2) fume was generated by hydrolysis of uranium hexafluoride (UF_6). This fume shows little tendency toward aggregation or chain formation in contrast to the uranium dioxide fume shown in the same figure.

Another excellent example of the electron microscope's usefulness has already been given in the first article of this series (*23*) where indispensable aid was given the solution of a perplexing toxicity problem involving three closely similar grades of beryllium oxide. Used in conjunction with other physicochemical methods and with toxicity determinations, the responsible toxic agent was unmistakably identified as the fluorescent grade; electron micrographs indicated this material to possess the greatest surface.

A relatively unexplored field in electron microscopy is the use of electron diffraction for positive identification of particulates similar to that obtained by X-ray diffraction (*24*) in the identification of causative particulates in silicosis.

Cascade impactor. The Cascade Impactor can be considered as a multiple-jet sampler historically related to the konimeter and similar single-orifice sampling devices. This instrument employs a series of jets of decreasing areas

* Illustration reprinted with permission of the Atomic Energy Commission from Chapt. 10 of "The Pharmacology and Toxicology of Uranium Compounds," NNES VI-I, edit. by C. Voegtlin and H. Hodge (McGraw-Hill Book Co., Inc., New York, 1949).

and collecting slides arranged in tandem. Streamline design and the use of rectangular orifices permit the continuous flow of an air stream through the instrument with a minimum of loss and with high collection efficiencies at each orifice.

Air is drawn through the instrument at constant rate (*e.g.*, 14 liters/min) and, since the orifice areas progressively decrease, the velocity and therefore the efficiency of separation of the particles at each stage increases. Particles are deposited on successive slides largely through their inability to follow the course of the air stream, a consequence of their relative momentum and the low viscosity of the air. Satisfactory retention of the particles on the collecting slides, however, requires the use of a thin adhesive coating* to minimize shattering and prevent losses.

The problems of shattering of larger particles at velocities required to impinge smaller sizes, prominent in the literature of single-jet sampling devices, are largely overcome. In addition, the size selectivity of such devices is used to advantage in the Cascade Impactor for segregating different-size fractions of the total particle distribution. The first stage removes the largest particles and each succeeding stage progressively removes a segment of the upper size range of the remaining distribution. Thus the total air sample is divided into several overlapping distributions, one on each stage.

Size-number distributions are determined by direct microscopic measurement of the samples collected on each stage. To calculate the total distribution, the individual stage distributions are then weighted in terms of the relative numbers of particles collected at each stage. Size-mass distributions may be calculated as a cube function of the size-number distribution.

The *special* advantage of the Cascade Impactor is that particle size-mass distributions can be determined by a chemical or physical analysis of the total particulate mass collected on each stage without resorting to counting the particles and measuring their diameters. This procedure of indirect analysis eliminates the most laborious and time-consuming factor in particle-size analyses and has enabled the Cascade Impactor to become practical for large-scale routine problems.

On the basis of theoretical and experimental considerations (*14*), it can be shown that the size-separation factor of significance in the operation of the Cascade Impactor is the relative mass of the particle rather than its measured size. Except for the first orifice, the corrected size-mass median at each stage (designated as the effective size-constant or stage-calibration value) and the slope of the size-mass distribution (on a logarithmic-probability plot) are functions of the sampling rate, the orifice characteristics, and the density of the particulates.

The stage-calibration value of the first orifice is a variable dependent upon the upper size limits of the sampled atmosphere. For a specific material and fixed sampling conditions, the stage-calibration values and distributions are constant. It is the relative amounts of material collected at each stage that determine the total size-mass distribution of any air sample. A simple procedure of weighting the stage-calibration values as a function of the integrated mass of material collected can be used to calculate the total size distribution. The use of a logarithmic-probability plot for this procedure facilitates the determination of the distribution parameters.

The first design of the Cascade Impactor has been described by May (*25*)

* Any nondrying tacky adhesive (*e.g.*, an alkyd resin) will serve, but the selection of a particular adhesive may be made depending upon the type of analysis which the samples ultimately undergo.

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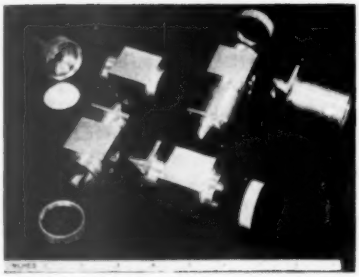

Disassembled unit showing 4 jets, filter-paper stage, screw caps and slide holder

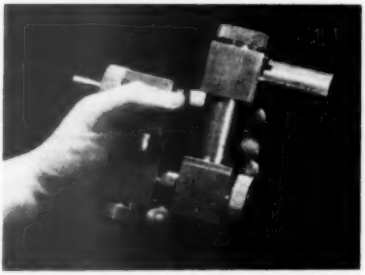

FIG. 7. Modified cascade impactor (assembled with sampling line)

as a four-jet instrument for sampling coarse aerosols (1–50 μ for materials of unit density). Sonkin (*26*) later designed a similar instrument of glass, the principal advantages being ease of construction and smaller orifices extending the lower size limits to 0.25 μ.

Significant improvements have been made by Laskin (*14, 27*) which consist of (1) a design allowing construction by precision machining and accurate duplication of instruments, high orifice tolerances, and minimization of internal losses, and (2) addition of a fifth, filter-paper stage. Addition of this stage was necessary to collect a relatively large population of small particles that escaped in the original instrument. The use of additional jets of finer sizes was found not to be practical.

The instrument known as the *Modified Cascade Impactor* also extended the range of the original instrument to the size distribution commonly encountered in most industrial problems. Figure 7 shows the assembled unit and the component jets in position for assembly.* The effective range of sizes sampled varies with the nature of the material sampled; however, excellent results are obtained for most substances with size ranges between 0.2 to 50 μ diameter. For particulates of smaller size ranges (*i.e.*, below 0.3–0.6 μ) the instrument is still a highly efficient sampler, although the size distribution cannot be adequately characterized. For characterization of these smaller size ranges, the thermal precipitator described later is the preferred instrument.

To determine the stage-calibration constants of this instrument accurately, a rather tedious procedure of indirect calculation and size measurement is required for each compound. The calibration procedure has been described for uranium dioxide dust atmospheres (*14*), and a simplified calculation has been developed for the conversion of the uranium dioxide values to those for use with other compounds and other sampling velocities. Verification of the validity of this calculation for beryllium sulfate mist has been made by direct electron microscopic measurements of simultaneously collected thermal precipitator samples. A mass-median diameter of 0.80 μ was obtained in comparison with a calculated value of 0.85 μ. Results with other compounds agreed similarly within the errors of the methods.

The procedure for determining the particle-size distribution of a uranium

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* Arrangements are now under way with Mine Safety Appliances, Pittsburgh, Pa., for the production of this instrument to rigid specifications. Calibration of the instrument for determining stage particle-size constants in many cases will be unnecessary. Standard values will be furnished with the instrument. Application of the instrument to most other dusts will then require only simple recalculation of these stage constants according to the relative density of the dust and sampling velocity.

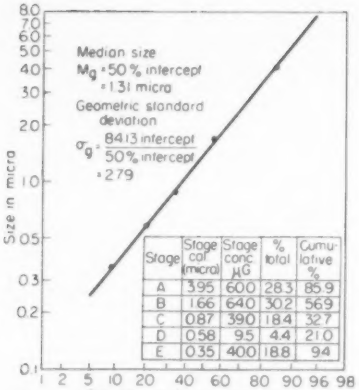
Median size
M_g = 50% intercept
= 1.31 micra
Geometric standard deviation
$\sigma_g = \frac{84.13 \text{ intercept}}{50\% \text{ intercept}}$
= 2.79
Size in micra
Percent less than stated size
Stage | Stage cal (micra) | Stage conc μG | % total | Cumulative %
A | 3.95 | 600 | 28.3 | 85.9
B | 1.66 | 640 | 30.2 | 56.9
C | 0.87 | 390 | 18.4 | 32.7
D | 0.58 | 95 | 4.4 | 21.0
E | 0.35 | 400 | 18.8 | 9.4

FIG. 8. Stage-distribution plot derived from Modified Cascade Impactor showing method of determining mass-median particle size and geometric standard deviation of a dust distribution

dioxide air sample collected with the Modified Cascade Impactor is illustrated in Fig. 8. The concentration at each stage expressed in micrograms is converted to a percentage of the total sample and integrated in terms of the cumulative percentage of mass belonging to the sizes that are less than the stage-calibration values of each stage. Total distribution is obtained by plotting stage-calibration values in micra against these cumulative percentage values on a logarithmic-probability grid. As indicated, the mass-median diameter and standard geometric deviation of 1.13 μ and 2.79 are directly obtained.

Air concentrations in terms of mg/m^3 can also be directly obtained by the Cascade Impactor since the sampling velocity and time are known. In the illustration cited, the sample was collected at 14 liters/min for 10 minutes which yielded a value of 1.5 mg U/m^3. This procedure, however, is unnecessarily involved unless particle size is also desired; the filter paper dust sampler yields concentration values directly with one analysis.

Application of the Modified Cascade Impactor has now been made for several years in the characterization of dust and mist atmospheres of uranium and beryllium compounds. In both laboratory and field problems, it has proved to be a sturdy instrument that produces rapid and reliable results. It may also be used for the size distribution analysis of a mixture of dusts, such as is frequently encountered in many industrial atmospheres. Results may be expressed in terms of one or more components, providing the chemical composition of the dust in question is known and analytical procedures are available for the components.

Thermal precipitator. For characterizing small particulates below the useful range of the Cascade Impactor, the most valuable instrument is the thermal precipitator. In this instrument, air is drawn at low velocity across a hot wire centrally located between two collecting surfaces. Precipitation of the particles occurs on the collecting surface because of the thermal repulsion resulting from the differential energy states of the gas molecules in the air stream.

The design developed by Green (*9*) has often been described (*1*, *2*). Efficiencies of 100% for particle sizes up to 20 μ have been claimed; however, with normal sampling velocities (7 ml/min), the upper size limits are of the order of 1–2 μ.

The slow sampling rate limits the usefulness of this instrument for concentration analysis to high atmospheric levels. The instrument is also of limited usefulness with compounds affected by heat. One advantage of the thermal precipitator is that it permits samples to be collected directly on electron microscope screens.* The procedure, however, requires the sur-

* This is also true of the electrostatic precipitator, but one has less assurance that the sample is unaffected by the method of collection.

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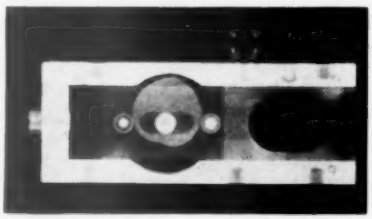
veying of a large number of fields because of a nonuniform distribution of particle sizes obtained on the collected sample.

This difficulty has been eliminated in the recent development of an oscillating thermal precipitator (*28*). The design based on suggestions of Green is illustrated in Fig. 9. Samples are precipitated on a moving specimen holder activated by a heart-shaped cam as illustrated by the X-ray photograph.

The nature of the improvement in the character of the sample is illustrated in Fig. 10 for a sodium chloride aerosol. On the left in Fig. 10 is a sample collected with a conventional thermal precipitator in contrast with the more uniformly dispersed sample collected with the oscillating thermal precipitator on the right. Particle-size and number analysis confirmed the uniformity of collection with respect to sizes. This permitted the use of a single, centrally located electron microscope screen for characterizing the original atmosphere. The production of a thin uniform sample of known geometry may also prove valuable for activity measurements in radioactive dust problems.

FIG. 9. Motor-driven oscillating thermal precipitator. Above: Assembled instrument showing specimen holders and filament. Below: X-ray photograph showing drive mechanism.



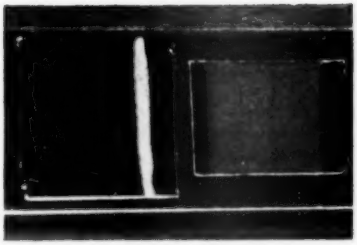


FIG. 10. Thermal precipitator samples of NaCl fume shown under slide. Left: By static model. Right: By oscillating model.

Measurement of homogeneous aerosols. War-stimulated research in bacteriological warfare, in the production of smoke screens, and in respirator testing placed an emphasis on the quantitative measurement of particle size and concentration of dilute, spherical, homogeneous aerosols of small size. This activity has resulted in the development of a variety of instruments involving the interference of a beam of light by particle droplets. LaMer and colleagues (*29*) developed a number of methods and two practical, field-tested instruments based on this principle.

One, the Slopometer, is a portable photoelectric meter on which is read the transmission at different wavelengths through an aerosol; the relative transmissions at two wave lengths yield the average particle-size value; the absolute transmission at one wave length, the concentration. The Slopometer is applicable only to spherical particles of relative small (about 1μ in diameter) but uniform size (within 10% variation from the average size).

The other instrument, the "Owl,"

depends upon the visual observation of the color of scattered light by fog or smoke particles. This is likewise a portable instrument and is designed chiefly for rapid measurement of average-particle-size small droplets homogeneous with respect to refractive index and size. The instrument has given reliable results for homogeneous aerosols of 1μ or less in diameter. By converting the instrument to a polarization photometer, droplets of smaller size (0.1–0.4 μ diameter) may be measured.

Gucker and associates (*30*) have developed a number of photoelectric particle counters applicable to homogeneous fogs and smokes, and Gucker has reviewed other methods (*31*) still in the experimental stage that appear promising. Some of their photoelectric counters may be used for measuring and controlling particulate concentrations. Like LaMer's, Gucker's instrument is capable of detecting 1 $\mu g/m^3$ of a homogeneous aerosol of spherical droplets of 0.3 μ diameter and is thus useful for testing penetration of aerosols through the most efficient respirator filters and gas-mask canisters. Other applications under investigation include counting of bacteriologic aerosols, detecting leaks into sterile atmospheres, or, by adaptation, counting liquid-suspended particles.

Another new type of particle counter based on electrostatic principles originating with Guyton (*32*) is applicable to particles, either wet or dry, of somewhat larger diameter, 2.5 μ or greater, but may be improved later to detect smaller sizes. Individual particles striking a wire produce pulses that can be amplified, and counting rates up to 1,800 per minute or 300 per liter have been attained. This counter is applicable to solid particles, but further experimentation is necessary before its suitability for general laboratory or field work is demonstrated. A possible use not found in most counters is the discrimination between particles of differing chemical composition.

Methods depending upon the optical and electrostatic effects are applicable in their present development to airborne spherical, uniformly sized particles (mists, condensation fogs, bacteria) and yield chiefly information on average particle size. Some are adapted to measure concentration. With the exception of the Owl and the Slopometer, none are as yet in a stage where they may be of service in the industrial plant and none are available commercially.

Measurement of Particulate Surface

Lately added to the armamentarium of the industrial toxicologist are the physicochemical methods of surface-area measurement. An intensified activity of particulates, evidenced by increased rates of oxidation and solubility and changes in electric and catalytic properties, can be directly correlated with the increased surface of small sizes. Correlation of surface-area data with toxicity studies, however, *requires a distinction between* the calculated or measured geometric surface and the frequently larger areas which include the fine internal structure and irregularities of the particles (porosity).

Many methods involving a variety of principles are available for surface-area measurements. These have been recently reviewed by Bikerman (*33*). For nonporous particulates possessing known geometrical shapes, the surface area can be calculated from the physical dimensions found by direct microscope measurement, sedimentation and ultracentrifuge studies, or by various air-permeability methods.

Methods which are more generally applicable for measuring the internal surface (porosity) have employed the phenomena of heat conductivity, heat of wetting, heat permeability, solution adsorption and low-temperature gas

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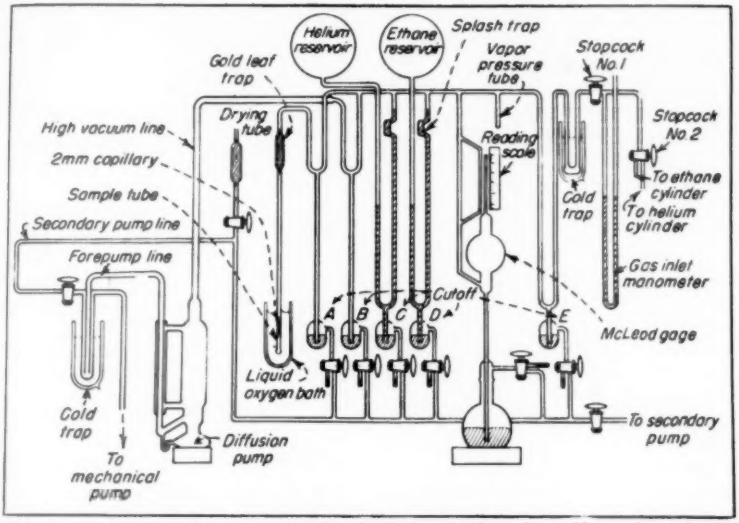

FIG. 11. Gas-adsorption apparatus for the determination of specific surface of solid particulates

adsorption. Most of these methods require large samples (above 50 mg) and are not directly applicable to the small quantities collected from toxic atmospheres.

In addition, several methods are limited by the physical and chemical nature of the particles, their non-homogeneity and relative packing characteristics.

The low-temperature gas adsorption method of Brunauer, Emmett, and Teller (*34*), and its modification by Wooten and Brown (*35*), is well suited to the toxicologic problem because of its capacity to measure the low surface areas of porous particles. The adaptation by Lauterbach *et al.* (*36*) of this technique to uranium dusts, utilizing ethane gas as the adsorbate, provides the required increase in sensitivity for the range of surface areas encountered in most toxic particulates (0.01 to 100 m^2/gm).

Accurate surface-area measurements expressed as area per unit weight (specific surface) have been obtained for a number of toxic dusts of uranium, beryllium and zirconium compounds. Although these values were determined largely from bulk samples (10–50 mg), the method is capable of utilizing samples as small as 1–2 mg and can be applied to atmospheric samples such as those collected with the electrostatic precipitator. Total areas as low as 10 cm^2 have been accurately measured. The method was verified within experimental errors with sized glass beads and specific surfaces calculated from microscopic measurements.

A typical gas-adsorption apparatus required for this method is shown in Fig. 11. Essentially it consists of a sample tube, gas reservoirs, a McLeod gage and several mercury seal valves. A dried sample is sealed in the system and evacuated to 10^{-5} mm of Hg or less. The adsorption of ethane is determined at the temperature of liquid oxygen (−183° C) using the McLeod gage as a gas buret. A gas charge is measured,

expanded into the system and then allowed to reach the adsorption equilibrium pressure. The sample is then isolated, more gas is added to the McLeod gage and the process repeated. In this way a pressure-volume isotherm is developed showing the volume of ethane adsorbed plotted against the relative equilibrium pressure.

Scale A on Fig. 12 illustrates the adsorption isotherm of ethane on a uranium dioxide dust sample at a temperature of −183° C. The data of Emmett and Brunauer (*34*) for an iron-alumina catalyst at a temperature of −195.8° C is replotted on scale B to demonstrate the similarity of the isotherms despite the large difference in the adsorbate vapor pressures. From the resulting isotherm and the Brunauer, Emmett and Teller (*34*) equation, it is possible to determine the volume of gas required to form a single molecular adsorbed layer on the particulate surface. The total surface of the sample is thus the product of the number of molecules required to form a single layer times the average cross-sectional area for an adsorbed molecule.

A convenient method of expressing surface irregularity is through the "porosity" concept which relates the surface area determined by the method mentioned above to the surface calculated from particle diameters measured optically (which excludes surface irregularities); high porosity values indicate large surface irregularities.

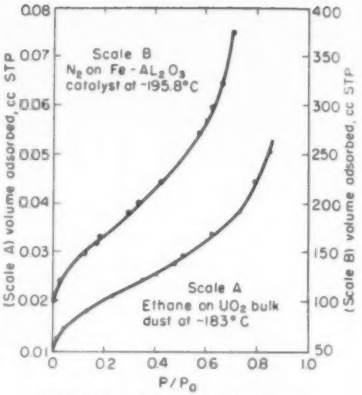

FIG. 12. Adsorption isotherms

Specific surface values by this method have been consistent with electron micrographs, solubility rates, and toxicity of fine particulates [*e.g.*, see (*23*)]. The results, however, are of questionable significance when applied to crystal hydrates and unstable compounds. Unfortunately, as yet, no comparative surface-area measurements are available on the same specimen using different methods.

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IN RECENT YEARS, several new particles have been discovered which are currently assumed to be "elementary," that is, essentially, structureless. The probability that all such particles should be really elementary becomes less and less as their number increases.

It is by no means certain that nucleons, mesons, electrons, neutrinos are all elementary particles and it could be that at least some of the failures of the present theories may be due to disregarding the possibility that some of them may have a complex structure.

—*E. Fermi and C. N. Yang.* Phys. Rev. **76,** *1739 (1949)*

Evaluation of Neutron Counter Efficiency

Expressions for the absorption rate of a long, cylindrical BF_3 thermal neutron counter imbedded in an infinite space of paraffin are determined for the case of constant rate of production of thermal neutrons throughout the paraffin space.

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THE NEUTRON absorption rate in a long, cylindrical, BF_3-filled detector imbedded in paraffin (or other diffusing medium such as water or carbon) can be related to the rate of production of thermal neutrons in the diffusing medium. This is done here for the case where the detector is not perfectly absorbing, but "gray."

The problem is similar to that of thermal utilization in a pile (*1*). That problem is treated by diffusion theory in the uranium where the absorption cross section is of the same order of magnitude as the scattering cross section. In BF_3, however, the absorption cross section is many times the scattering cross section, and diffusion treatment is not valid.

The fundamental problem is that of a very long cylinder (radius r_c and height h) of BF_3 imbedded in an infinite space of paraffin, with an annular ring of free space between cylinder and paraffin such that the coaxial cylindrical hole in the paraffin is of radius r_p. Throughout the paraffin there is a constant production rate of thermal neutrons. The resulting absorption rate in the BF_3 cylinder is determined by using diffusion theory in the paraffin and a boundary condition determined by matching fluxes at the paraffin surface.

For a gray cylinder the net flow in paraffin will be small; thus the neutrons will be moving almost isotropically and diffusion theory (*2*) in the paraffin will be quite good. The diffusion equation is

$$L^2\nabla^2 N(\mathbf{r}) - N(\mathbf{r}) = -\tau Q(\mathbf{r}) \quad (1)$$

where, in general,

$$N(\mathbf{r}) = \int_0^\infty n(\mathbf{r},\mathbf{v})d\mathbf{v}$$

$$Q(\mathbf{r}) = \int_0^\infty q(\mathbf{r},\mathbf{v})d\mathbf{v}$$

$$L^2 = \frac{\tau \int_0^\infty (vl/3)n(\mathbf{r},\mathbf{v})d\mathbf{v}}{N(\mathbf{r})}$$

and $N(\mathbf{r})$ is the space density of thermal neutrons; Q (here assumed independent of $\mathbf{r}$) is the rate of production of thermal neutrons per unit volume; L is the diffusion length in paraffin; v is the neutron velocity; l is the transport mean free path (*2*) of neutrons in paraffin; and τ is the mean life of a thermal neutron in paraffin.

The solution in cylindrical coordinates with radial symmetry is*

$$N(r) = Z_0(ir/L) + Q\tau \quad (2)$$

Since $N(\infty)$ must be finite, and since the Hankel functions are the only Bessel functions of imaginary argument which remain finite for infinite argument, then

$$N(r) = q\tau[1 - CiH_0^{(1)}(ir/L)] \quad (3)$$

* See Jahnke and Emde, "Tables of Functions," (Dover Publications, New York, 1945) for the Z_0, $H_0^{(1)}(iz)$, and $H_1^{(1)}(iz)$ notations and relations.

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where C is the remaining arbitrary constant to be evaluated.

For convenience write

$$H_0 = iH_0^{(1)}(ir_p/L)$$
$$H_1 = -H_1^{(1)}(ir_p/L)$$

Then the net flow into the counter is

$$S(r_p) = \int_0^\infty \frac{lv}{3} \nabla n(r_p,v)dv = \frac{L^2}{\tau} \nabla N(r_p) = QLCH_1 \quad (4)$$

since the diffusion coefficient is $lv/3$ Then

$$\frac{S(r_p)}{N(r_p)} = \frac{L}{\tau} \frac{CH_1}{1 - CH_0} \quad (5)$$

If the counter were "black," the counter absorption could be obtained by setting $N(r_p) = 0$, solving for C, and evaluating $S(r_p)$. However, the usual arrangement is such that the absorption mean free path in BF_3 is several times as large as r_c so that the counter is by no means "black." Thus it must be considered that neutrons leave, as well as enter, the counter with a probability of diffusing in the paraffin and re-entering the counter before being captured in paraffin.

Evaluation of the Constant C

Another expression for $S(r_p)/N(r_p)$ will be found in terms of known quantities by considering in more detail what happens at the surface of the paraffin.

Let $f(\mu,v)dsd\omega dv$ be the number of neutrons of velocity v within dv that flow per unit time through a paraffin surface element ds, in the element of solid angle $d\omega$, with velocity direction at the angle μ from the inward radius. Examination will show that $\cos \mu = \cos\theta\cos\phi$ and $d\omega = \cos\theta d\theta d\phi$; where ϕ is the azimuthal angle from the inward radius (Fig. 1) and θ is the angle between velocity direction and a transverse plane of the cylinder.

In accordance with the diffusion theory approximation (*2*), use the first two terms in the expansion in spherical harmonics of the neutron velocity direction distribution, so that

$$f(\mu,v) = \frac{1}{4\pi} vn(r_p,v)[1 + 3b(v) \cos \mu] \cos \mu \quad (6)$$

If the result is $3b \ll 1$, i.e., that the neutrons move nearly isotropically between collisions in paraffin with a slight predominance of movement toward the counter, then the diffusion approximation in the paraffin will be justified.

By integrating Eq. 6 over all solid angle, the net flow into the counter is

$$s(r_p,v) = vb(v)\, n(r_p,v) \quad (7)$$

The quantity $b(v)$ will be found by evaluating the flux out of the cylinder in two ways and equating. The first is to integrate Eq. 6 over $\pi/2 \leq \mu \leq \pi$, as in Eq. 8. The second is to find the flux arriving at a surface element of the cylinder after traversing the cylinder, as in Eq. 9.

The number of neutrons leaving the paraffin hole per unit time and unit surface is

$$E(v) = \int_{\pi/2}^{\pi} f(\mu,v)2\pi \sin \mu \, d\mu = [1 - 2b(v)]vn(r_p,v)/4 \quad (8)$$

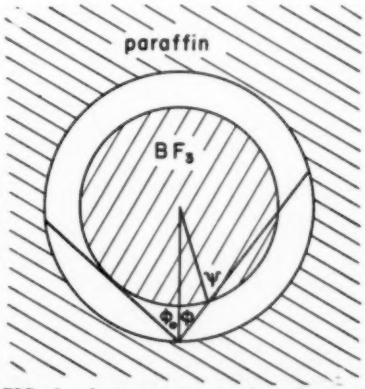

FIG. 1. A transverse section showing the coordinate system used. θ is the angle between the velocity direction and the plane of this paper

But $E(v)$ may also be expressed as

$$E(v) = \int f(\mu,v) \exp.\ (-d(\theta,\phi)/\lambda) d\omega \quad (9)$$

where the integration covers all paths through the cylinder to the surface element under consideration; $d(\theta,\phi)$ is the path length through BF_3, and λ is the absorption mean free path* for neutrons in BF_3. By equating Eqs. 8 and 9, the $b(v)$ is found.

A B^{10} capture cross section of 3,820 barns† at 2,200 meters/sec gives the value $\lambda = 10.7/p$ cm for a partial pressure p atmospheres of $B^{10}F_3$ at 300° K. It will be convenient to define $a = 2r_c/\lambda$ which is a measure of the counter absorption. Thus $a(= r_c p/5.55$ at 2,280 meters/sec) is often much less than unity under laboratory conditions. Also let $k = r_c/r_p$. The situation $a \ll$ unity is necessary for the validity of the diffusion approximation and also simplifies the evaluation of Eq. 9 through series expansion of the exponential.

Figure 1 shows $k \sin \psi = \sin \phi$. Define $\phi_0 =$ arc sin k as the angle at which a neutron just misses the BF_3 cylinder. Then Eq. 9 may be written

$$E(v) = \frac{n(r_p,v)v}{4}[1 + 2b(v)] - n(r_p,v)v[I_1(v) + 3b(v)I_2(v)] \quad (10)$$

where

$$I_1(v) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} d\theta \cos\theta \int_0^{\phi_0} d\phi \cos\theta \cos\phi[1 - e^{\frac{-a(v)\cos\psi}{\cos\theta}}] \quad (10a)$$

$$I_2(v) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} d\theta \cos\theta \int_0^{\phi_0} d\phi \cos^2\theta \cos^2\phi[1 - e^{\frac{-a(v)\cos\psi}{\cos\theta}}] \quad (10b)$$

Equating Eqs. 8 and 10 gives

$$b(v) = \frac{I_1(v)}{1 - 3I_2(v)} \quad (11)$$

* The only process of importance in BF_3 is B^{10} capture with negligible capture in B^{11} and negligible scattering in BF_3.

† Reference 4 gives 703 barns at 2,200 meters/sec for a natural boron mixture. Assuming no B^{11} capture and 18.4% B^{10} in a natural mixture gives 3,820 barns for B^{10} capture.

In a later section, a consideration of thermal source distribution in energy indicates that the flux of neutrons entering the counter should be Maxwellian in velocity distribution since most neutrons entering the counter have undergone at least several collisions with hydrogen—enough very nearly to establish thermal equilibrium with the paraffin. Then, similarly to Eq. 8, the flux into the counter is

$$Av^2e^{-\alpha v^2}dv = \frac{n(r_p,v)v}{4}[1 + 2b(v)]dv \quad (12)$$

where A and α are constants which will soon be replaced.

$$N(r_p) = \int_0^\infty n(r_p,v)dv = 4A\int_0^\infty \frac{1}{1 + 2b(v)} v^2e^{-\alpha v^2}dv \quad (12a)$$

and from Eq. 7

$$S(r_p) = \int_0^\infty s(r_p,v)dv = 4A\int_0^\infty \frac{b(v)v}{1 + 2b(v)} v^2e^{-\alpha v^2}dv \quad (12b)$$

Hence

$$\frac{S(r_p)}{N(r_p)} = \frac{\int_0^\infty \frac{b(v)v}{1 + 2b(v)} v^2e^{-\alpha v^2}dv}{\int_0^\infty \frac{1}{1 + 2b(v)} v^2e^{-\alpha v^2}dv} = \frac{k(av)}{4}\rho \quad (13)$$

where Eq. 13 defines ρ, the ratio of the two velocity integrals; and (av) is independent of v, namely, inserting the definition of a,

$$av = 2r_cv/\lambda = 2r_c/\tau_B \quad (13a)$$

where τ_B is the lifetime of a neutron in the BF_3 counter.

From Eqs. 5 and 13, C may now be expressed in terms of given quantities and the ratio ρ, and Eq. 4 will give the counter absorption rate R. Neglecting end effects

$$R = 2\pi r_p h Q L C H_1 = QV\frac{\tau}{\tau_B}\frac{\rho}{1 + \frac{k^2}{2}\frac{\tau}{\tau_B}\left(\frac{r_p}{L}\frac{H_0}{H_1}\right)\rho} \quad (14)$$

where V is the BF_3 volume.

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The ratio τ/τ_B is independent of neutron velocity and has the value

$$\frac{\tau}{\tau_B} = 3.37p\frac{295}{T\rho_p} \qquad (14a)$$

where p is the partial pressure of $B^{10}F_3$, T its absolute temperature and ρ_p the paraffin density. The numerical factor depends only on the ratio of the neutron capture cross sections of B^{10} and H, not on their absolute value. It is calculated above taking $\sigma_{B^{10}}/\sigma_H = 1.205 \times 10^4$ and assuming 2.08 hydrogen atoms per carbon atom in paraffin.

Another expression for Eq. 14 is

$$R = Q(2\pi r_p Lh)\frac{H_1}{H_0}\frac{\frac{k^2}{2}\frac{\tau}{\tau_B}\left(\frac{r_p}{L}\frac{H_0}{H_1}\right)\rho}{1+\frac{k^2}{2}\frac{\tau}{\tau_B}\left(\frac{r_p}{L}\frac{H_0}{H_1}\right)\rho} \qquad (14b)$$

For the case $r_p/L \ll 1$, $Q2\pi r_p Lh$ is the number of neutrons produced per second in an annular ring of thickness L surrounding the paraffin hole. The fraction following this quantity is then the fraction of all these neutrons that is actually absorbed in the counter. As indicated immediately after Eq. 5 on page 33, if the counter were "black" and $N(r_p) = 0$, then

$$R = Q(2\pi r_p Lh)\frac{H_1}{H_0}$$

The quantity $(r_p/L)H_0/H_1$ is plotted in Fig. 2.

Evaluation of Integrals

Equation 14 is the required expression for the counter absorption rate R if ρ is evaluated. From Eqs. 11 and 13

$$\rho = \int_0^\infty \frac{I_1\Big/\frac{ka}{4}}{1+2I_1-3I_2} v^2 e^{-\alpha v^2}dv \Bigg/ \int_0^\infty \frac{1-3I_2}{1+2I_1-3I_2} v^2 e^{-\alpha v^2}dv \qquad (15)$$

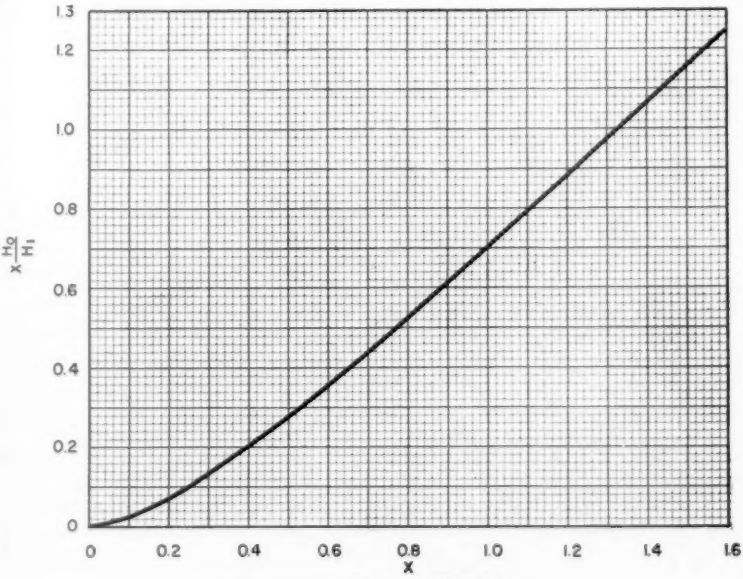

FIG. 2. Plot of $x\frac{H_0}{H_1} = x\frac{iH_0^{(1)}(ix)}{-H_1^{(1)}(ix)}$ vs x

Turning to the evaluation of I_1 and I_2, it is tempting to expand the exponentials in Eqs. 10*a* and 10*b* in power series in the small quantity $a(v)$. This, however, cannot be done in a straightforward manner, since the exponents contain $\cos\theta$ in the denominator, and this quantity may become zero. Therefore, break up the integrals over θ into two parts, from 0 to θ_0 and θ_0 to $\pi/2$, and choose θ_0 such that

$$\cos\theta_0 = a/r \qquad (16)$$

with r a number (later chosen to be 4). Then, for $\theta < \theta_0$, the exponent never exceeds r and the exponential can be expanded; the contribution of the part $\theta > \theta_0$ becomes very small. Thus,

$$I_1(v) = \frac{k}{\pi}\sum_{m=1}^{\infty} -\frac{[-a(v)]^m}{m!} \int_0^{\theta_0} \cos^{2-m}\theta\, d\theta \int_0^{\pi/2} \cos^{m+1}\psi\, d\psi + \frac{k}{\pi}\int_{\theta_0}^{\pi/2} d\theta \cos^2\theta \int_0^{\pi/2} d\psi \cos\psi \left[1 - e^{-\frac{a(v)\cos\psi}{\cos\theta}}\right] \qquad (17)$$

The evaluation of the first integral for $m = 1$, 2, and 3 is elementary. For higher m, the main contribution comes from θ near θ_0, and it is permissible to replace $d\theta$ by $\sin\theta\, d\theta$, an approximation which causes an error of relative order a^2 in these terms, and an absolute error of order a^5 in I_1. Terms of this order are neglected in this discussion. Then Eq. 17 becomes

$$I_1 = \frac{ka}{4}\left[1 - \frac{2}{3}a + \frac{a^2}{8}\left(\ln\frac{8}{a} + r_1\right) + 0(a^4)\right] \qquad (18)$$

where the "remainder" r_1 is (neglecting terms of relative order a^2 throughout)

$$r_1 = \frac{32}{\pi}\sum_{m=4}^{\infty}\frac{(-1)^{m-1}}{m!}\frac{r^{m-3}}{m-3} \int_0^{\pi/2}\cos^{m+1}\psi\, d\psi + \left[\frac{32}{3\pi r} - \frac{4}{r^2}\right] + \frac{32}{\pi}\int_0^{1/r} x^2 dx \int_0^{\pi/2} d\psi \cos\psi \left(1 - e^{-x\cos\psi/x}\right) \qquad (18a)$$

The first term (sum) represents the terms $m \geq 4$ in the series in Eq. 17;

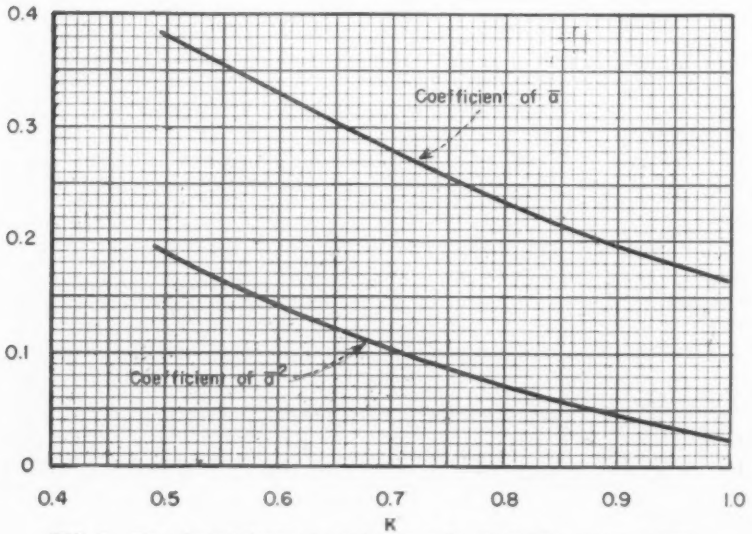

FIG. 3. Plot of coefficients of a and $\bar{a}^2$ in ρ, Eq. 22, for the case $\bar{a} = 0.20$

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the second (square bracket) comes from the fact that the integrals $m = 1$ and 2 are extended only to θ_0 and not to $\pi/2$; the last term (integral) is the last term of Eq. 17, with cos θ replaced by ax. The remainder (Eq. 18*a*) can be evaluated for any r and should give a result independent of r. Choose $r = 4$; then the magnitude of the terms in the sum will decrease uniformly with m, and the sum of all the terms in the series, from any term m_0 on, will be less than the term m_0. Evaluation with $r = 4$ gives $r_1 = -0.018 \pm 0.001$.

Similarly

$$I_2(v) = \frac{k}{\pi} \sum_{m=1}^{\infty} \frac{-[-a(v)]^m}{m!} \int_0^{\pi/2} \cos^{3-m}\theta \, d\theta \int_0^{\pi/2} (1 - k^2 \sin^2\psi)^{1/2} \cos^{m+1}\psi \, d\psi \quad (19)$$

This may be evaluated in the same way as Eq. 17 and the result is, to order a^3,

$$I_2 = \frac{ka}{4}\left[\frac{2}{3}k_0 - \frac{3}{8}k_1 a + \frac{8}{45}k_2 a^2\right] \quad (20)$$

where the definitions are

$$k_0 = \frac{1+k^2}{2k^2}E(k) - \frac{1-k^2}{2k^2}K(k)$$

$$k_1 = \frac{4k^2-1}{3k^2}\frac{2}{\pi}\text{arc sin } k + \frac{1+2k^2}{3k^2}\frac{2}{\pi}(1-k^2)^{1/2}$$

$$k_2 = \frac{1}{8k^4}[(7k^2 + 3k^4 - 2)E(k) - 2(3k^2 - 1)(1 - k^2)K(k)]$$

and $K(k)$ and $E(k)$ are complete elliptic integrals of the first and second kind, respectively. That is,

$$K(k) = \int_0^{\pi/2} (1 - k^2 \sin^2\psi)^{-1/2} d\psi$$

$$E(k) = \int_0^{\pi/2} (1 - k^2 \sin^2\psi)^{1/2} d\psi$$

It is to be noted that I_1 is needed to one higher order in a than is I_2 because I_1 occurs by itself in Eq. 15 (and is of order a) while I_2 occurs only in combination with 1. This makes it permissible to neglect terms of order a^4 in I_2, thus obviating the evaluation of all terms analogous to the remainder term r_1 in I_1, Eq. 18*a*. The error due to this neglect is the same as that caused by neglecting terms of order a^5 in I_1, and the result for ρ will be correct up to and including terms of relative order a^3. In the following, however, the (very small) term of that order (last term in Eq. 20) will be dropped.

In taking the integrals over velocity in numerator and denominator of Eq. 15, it must be remembered that the average of a^2 is not the same as the square of a_{av}. However, it is convenient to express the result in terms of $\bar{a}$, the average of a. Remembering that a is proportional to the capture cross section of boron, and thus inversely proportional to the velocity, $\bar{a}$ corresponds to the *inverse mean* velocity,

$$\bar{v} = \int_0^\infty v^2 e^{-av^2} dv \Big/ \int_0^\infty v e^{-av^2} dv = (\pi/4)^{1/2} v_0 \quad (21)$$

with v_0 the "Maxwell velocity"

$$v_0 = 1/a^{1/2} = (2kT/M)^{1/2} \quad (21a)$$

Since the neutron temperature in paraffin is, experimentally, about 400° K, v_0 is 2,580 meters/sec, and $\bar{v} = 2{,}280$ meters/sec. Taking the mean free path in boron, λ, for this velocity gives $\bar{a} = r_4 p/5.55$.

In terms of $\bar{a}$,

$$\rho = 1 - \bar{a}\left(\frac{2}{3} - \frac{1}{2}kk_0\right) + \frac{\pi}{16}\bar{a}^2\left[\left(\ln\frac{16}{\pi^{1/2}\bar{a}} + r_2 - 1\right) - \frac{9}{4}kk_1 + 4k\left(1 - k_0 - \frac{2}{\pi}\right)\left(\frac{2}{3} - \frac{1}{2}kk_0\right)\right] \quad (22)$$

and $r_2 = r_1 + 1 - \ln 2 - \frac{1}{2}\gamma$ (22*a*)

with γ Euler's constant. Evaluation gives $r_2 < 0.0007$ which is negligible. Figure 3 shows the coefficients of $\bar{a}$ and $\bar{a}^2$ in Eq. 22 plotted against k.

For $k = 1$, $k_0 = k_1 = 1$ and, dropping r_2,

$$\rho = 1 - \frac{\bar{a}}{6} + \frac{\pi}{16}\bar{a}^2 \left[\left(\ln \frac{16}{\pi^{1/2}\bar{a}} - 1\right) - \frac{9}{4} - \frac{4}{3\pi}\right] \quad (23)$$

It may be seen from Eq. 11 that $b \sim ka/4$, so that for $\bar{a} \ll 1$ the diffusion approximation is good. Therefore $a = r_c p/5.55 \gtrsim 1/5$ will give a reasonable accuracy in ρ.

It is further interesting to note that, if the denominator $1 + 2b(v)$ is omitted in the definitions given in Eqs. 12*a* and 12*b*, the first two terms in Eq. 22 remain unaffected and the complete formula for ρ is changed to

$$\rho' = \rho - \frac{1}{2}\bar{a}^2\left(\frac{\pi}{2} - 1\right)k\left(\frac{2}{3} - \frac{1}{2}kk_0\right) \quad (24)$$

The table below gives sample values of the parameters involved in Eq. 14 for various values of p, r_p/L, and k.

Interpretation

The meaning of Eq. 14 may be seen after rewriting the quantities

$$\left(1 + \frac{k^2}{2}\frac{\tau}{\tau_B}\frac{r_p}{L}\frac{H_0}{H_1}\rho\right)^{-1} = 1 - CH_0$$

and

$$\rho = \int_0^\infty \frac{I_1' + 2bI_2'}{1 + 2b} v^2 e^{-av^2} dv \Big/ \int_0^\infty \frac{1}{1 + 2b} v^2 e^{-av^2} dv$$

where $I_1' = \frac{4}{ka} I_1 \sim 1$

and $I_2' = \frac{4}{ka}\frac{3}{2} I_2 \sim k_0 \sim 1$

Then Eq. 14 becomes

$$R = QV\frac{\tau}{\tau_B}(1 - CH_0)\rho$$

The leading term in this counter absorption rate, $QV\ \tau/\tau_B$, is just the absorption rate by a detector (*3*) in the interior of paraffin when the detector is so thin as to modify negligibly the density of neutrons. There are three main corrections to this leading term: (a) the depression of neutron density at the paraffin surface due to the sink created by the counter—as represented by CH_0; (b) the addition to R in the anisotropy term $2bI_2'$ in ρ—this anisotropy being caused by absorption in the counter which "draws" neutrons into the counter; (c) the reduction in R expressed in the two negative $a(v)$ terms in ρ due to the self-absorption by the counter; the other $a(v)$ terms in ρ originate from extensions of (c), i.e., reduction of self-absorption by self-absorption, *etc.*

The two latter corrections to R are both proportional to a and are hard to separate in higher orders in a; in the first order they tend to compensate, with the self-absorption effect being

Sample Values of Parameters Involved in the Absorption Rate

$$R = QV\frac{\tau}{\tau_B}\rho \Big/ \left(1 + \frac{k^2}{2}\frac{\tau}{\tau_B}\frac{r_p}{L}\frac{H_0}{H_1}\rho\right)$$

(Taking $L = 2.1$ cm and $\rho_p = 0.90$ gm/cm³)

p atm.	$\frac{r_p}{L}$	k	$\bar{a}$	ρ	$\frac{\tau}{\tau_B}$	$\frac{k^2}{2}\frac{\tau}{\tau_B}\frac{r_p}{L}\frac{H_0}{H_1}\rho$
0.50	0.80	0.50	0.076	0.973	1.87	0.120
0.50	0.80	1.0	0.151	0.977	1.87	0.481
0.50	0.40	0.80	0.060[5]	0.987	1.87	0.120
0.50	1.2	0.80	0.182	0.960	1.87	0.506
0.10	0.80	0.80	0.024	0.995	0.374	0.0625
1.0	0.80	0.80	0.242	0.945	3.74	0.625

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slightly greater. The sink effect (a) is essentially determined by properties of the paraffin rather than of the counter (except that the total absorption of the latter enters by way of the factor r_c/τ_B) and of the correction factor ρ. Of course, $1 - CH_0$ is positive definite. The sink effect is in general greater than the self-absorption.

Thermal Source Distribution in Space

In many experimental arrangements fast neutrons are moderated in a hydrogenous medium to thermal energies; the resultant distribution in space and velocity is represented by q. It may be shown that the counter has small probability of detecting a thermal neutron that originates at a distance greater than L from the paraffin surface, and since the thermal source strength varies rather slowly with distance from the fast neutron source, q has been taken constant over the paraffin space. This assumption is most useful for a fast source of more than several Mev energy for which the "slowing-down length" is large compared to $(r_p + L)$.

Thermal Source Distribution in Energy

In homogeneous paraffin, the energy distribution of neutrons is experimentally known to be Maxwellian, but with an effective temperature (4) about 100° higher than room temperature, i.e., about 400° K. This result was used in evaluating $\bar{v}$, Eq. 21; it is interpreted as being caused by the preferential capture of very slow neutrons, so that the neutrons emerging from the counter will on the average be faster than the neutrons in undisturbed paraffin. However, a few collisions with hydrogen atoms will probably restore the original energy distribution, and we have assumed that this will take place before the neutrons return to the counter, making the current entering the counter Maxwellian.

To estimate the possible error caused by this assumption, the value ρ would have in Eq. 24 if the average neutron distribution at the counter (average between entering and outgoing current) were Maxwellian has been calculated. With the assumptions $\bar{a} = 0.20$, k between 0.8 and 1, the correction term in Eq. 24 is 0.2%, which is very small. The actual correction is probably still smaller but in the opposite direction (reduction of counting rate R) because the incident neutrons have already somewhat higher energies than those in pure paraffin. A further correction, in the opposite direction and probably still smaller, will then arise from the fact that the diffusion length L is greater if the velocity is higher than in the Maxwellian distribution; this makes the denominator in Eq. 14 smaller and increases R.

Effect of Counter Wall

So far in calculation, the counter wall has been replaced by free space. An estimate of the error due to this can be made. For brass, of 70% Cu, 30% Zn, suitable cross sections (5) give a scattering mean free path of 2.1 cm and an absorption mean free path of 4.9 cm. A typical wall thickness is 0.05 cm, giving an absorption of 2% for a straight traversal.

The effect of scattering is very small, because scattering out of the counter at the near wall is very nearly compensated by scattering back into the counter at the far wall. Consider two unscattered trajectories $a \rightarrow b$ and $c \rightarrow d$ intersecting in the counter wall. If the scattered trajectory $a \rightarrow d$ is as probable as $c \rightarrow b$, scattering will not change the angular distribution of flux. This will be the case under the following circumstances: (a) isotropic scattering in the wall, (b) near compensation of the cos μ term in the flux by the obliquity factor in the wall, (c) little absorption in BF_3. Since these con-

ditions are nearly satisfied within the validity of this calculation, the effect of scattering in the wall is negligible.

Absorption is slightly more important. It acts as if the counter absorption were increased from a to $a(1 + x)$ where x is the ratio of wall absorption to counter absorption. But only a fraction $1/(1 + x)$ of all absorptions leads to counts. It is easily seen that:

1. The $\bar{a}$ in Eq. 22 for ρ should be replaced by $\bar{a}(1 + x)$.

2. The ρ occurring in the denominator of Eq. 14 should be multiplied by $1 + x$.

3. Otherwise Eq. 14 is unchanged.

The effect of **1** is usually less than one percent; that of **2** may be a few percent. Since **2** is more important than **1**, x may be estimated so as to be correct for effect **2**; for this purpose set

$$x = \frac{V_{\text{wall}}/\tau_{\text{wall}}}{V_{\text{boron}}/\tau_{\text{boron}}} = \frac{N_{\text{wall}}\sigma_{\text{wall}}}{N_B\sigma_B} \quad (25)$$

with V the volume, N the number of atoms and σ the cross section. For a wall thickness $t = 0.05$, counter radius $r_c = \frac{1}{2}$ in., B^{10} pressure $p = 1$ atm, we get $x = 0.2$.

* * *

The author wishes to express his thanks to Professor H. A. Bethe for suggesting and guiding these considerations.

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DESIGN OF VIBRATING CAP

There is considerable need for a sensitive, stable instrument for many radiation detection problems. Design considerations for a recording electrometer with a sensitivity of 10^{-15} amperes are discussed here.

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FOR CONTINUOUSLY MONITORING and recording radiation from radioactive areas and processes, it is necessary to have a sensitive electrometer with very good stability. D-C amplifiers have been found to be insufficiently stable for long period operation because of changing vacuum tube and power supply characteristics. Fiber-type electrometers are not adaptable to continuous recording use because of the re-charging needed and the complicated detecting mechanisms required.

One satisfactory electrometer for this type of application is the vibrating capacitor electrometer. The theory for this type of electrometer has been explained in a previous article [H. Palevsky, R. K. Swank, R. Crenchik, *Rev. Sci. Instr.* **18**, 298 (1947)]. This article describes a particular system and reviews the design considerations investigated in making the instrument as stable and rugged as possible.

OPERATING PRINCIPLES

Figure 1 is a photograph of the complete unit. In Fig. 2 is shown a block diagram of the electrometer. The

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preamplifier consists of a high input impedance amplifier stage followed by cathode follower. The a-c amplifier is a modified 4-stage Brown Instruments amplifier* and, together with the instrument slidewire, motor, and indicator, is present in the form of a Brown strip chart recorder. The power supply provides d-c power for the preamplifier and a-c power for the vibrating capacitor.

C_1 is the vibrating capacitor which has two circular plates. The upper plate is fixed and the lower plate is vibrated at 60 cps by a coil and a soft iron armature. The voltage across a capacitor of capacitance C is $V = Q/C$ where Q equals the charge on it. In our case C is being varied in accordance with the following:

$$C = \frac{K}{D + A \sin \omega t}$$

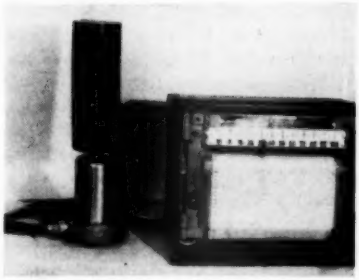

FIG. 1. Vibrating capacitor electrometer and chart recorder

where D is the average distance between plates and A is the amplitude of variation of the lower plate. If the resistors R_2 and R_3 are large so that the charge on the vibrating capacitor is essentially constant during a period,

$$V = \frac{QD}{K} + \frac{QA}{K} \sin \omega t$$

The input current from any high impedance source, such as an ionization chamber or pH electrodes, flows through resistor R_1 and through the measuring

* A standard Brown Instrument Company amplifier converts d-c to a-c by means of a chopper and then has a step-up transformer followed by 4 stages of gain. Here the chopper is omitted and it is used as an a-c amplifier.

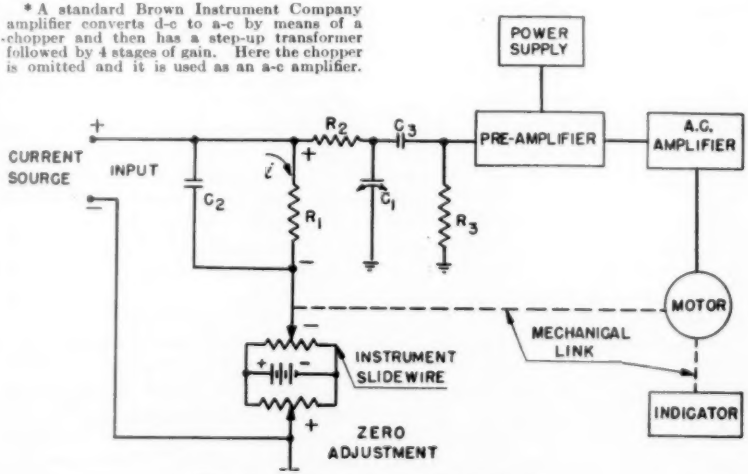

FIG. 2. Block diagram of electrometer

circuit, consisting of the instrument slidewire, zero adjustment and associated resistors, to ground. Since the input resistor R_1 is of the order of 10^{10} ohms and the measuring circuit about 200 ohms to ground, most of the voltage drop will appear across the input resistor. If the recorder is on zero and a current is then made to flow through the input resistor, the resulting voltage drop will charge the vibrating capacitor C_1. The vibrating capacitor then generates an a-c signal which is amplified by the preamplifier, and further amplified by a 4-stage a-c amplifier.

The output of the amplifier is used to drive the two-phase balancing motor which drives the indicator and pen recorder. Since the phase of the vibrating capacitor depends on the polarity of the d-c signal impressed on it, the motor then drives in a direction to balance the system. When the system is balanced, the voltage from the slidewire contactor to ground is equal and opposite to the voltage across the input resistor, so that the voltage between the top of R_1 and ground is zero and no charge appears on the vibrating capacitor. Thus, there is no signal generated to drive the motor.

Zero Adjustment

A zero adjustment, shown in Fig. 2, is made by means of 10-turn helical potentiometer which is used to compensate for the contact potential of the vibrating capacitor. If there is a difference in the work functions of the two capacitor plates, it will appear as a charge on the capacitor which will give a displaced zero for which the potentiometer will correct. The recorder chart and scale are linearly calibrated, -10 to 100, the minus readings being used to facilitate adjustment of the zero.

A decade range switch provides the instrument with three ranges. The voltage spans represented are -1 to 10 millivolts, -10 to 100 millivolts, and -100 to 1,000 millivolts. Thus, with a 10^{11} ohm resistor as an input resistor, the full-scale current ranges are 10^{-13}, 10^{-12} and 10^{-11} amperes.

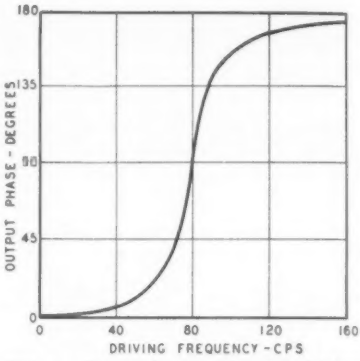

FIG. 3. Phase of output signal vs driving frequency for vibrating capacitor

DESIGN CONSIDERATIONS

Frequency of Vibration

The vibrating capacitor is driven at a frequency of 60 cycles per second—line frequency—and is consequently quite stable. The avoidance of a separate oscillator eliminates troubles sometimes encountered in vibrating capacitor electrometers using low-frequency oscillators. There is a tendency for them to drift or oscillate at a harmonic frequency.

The vibrating capacitor has been designed with a resonant frequency of approximately 80 cps, so that at 60 cycles there will be little change in the phase of the output signal with a change in line frequency, as can be seen from Fig. 3. For a vibrating capacitor operating at resonant frequency, the change in phase of the output signal is very large with a small change in line frequency. Maintenance of phase relationships is very important since the Brown strip chart recorder uses a 2-phase motor and the torque output

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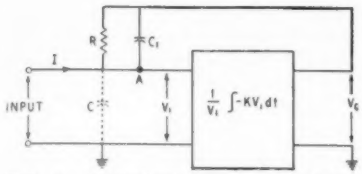

FIG. 4. Equivalent circuit of electrometer

is dependent on the relative phase of the voltages on the two windings.

Choice of Resistor Values

The largest utilized value of the input resistor is 10^{11} ohms. It was found that 10^{12}-ohm resistors were sometimes noisy and erratic. This fixed the minimum span of the instrument at 11 millivolts since it has been decided that 10^{-13} amperes should be the most sensitive range. This sensitivity is sufficient for most applications where a steady deflection type of instrument is needed.

The sensitivity of the instrument can be extended to 10^{-16} amperes by using the "rate-of-charge" method. The steady deflection type of indication was chosen partly because it permits the use of limit switches to operate at a predetermined current level, corresponding to a selected level of radiation when the electrometer is used with an ionization chamber. Another advantage is that the magnitude of the current is indicated almost immediately, the speed of indication being limited only by the speed of response of the instrument. Computing and timing required for the rate-of-charge method are avoided.

Narrow Bandwidth

Since noise limits the sensitivity of a vibrating capacitor electrometer, the bandwidth should be made as narrow as possible. In order to achieve this, a parallel T network* is used around the third stage of the 4-stage a-c amplifier which gives a bandwidth of 5 cps at 60 cps. Even though the motor is two-phase and responds only to 60 cycles from the amplifier, any frequency is capable of overloading the amplifier and causing decreased sensitivity.

System Stability and Response

The servo system consisting of amplifier, 2-phase motor, instrument slidewire, and preamplifier input circuit, is stabilized by placing a capacitor C_2 in parallel with the input resistor. This can be seen by considering the equivalent circuit of the complete system in Fig. 4. If we assume the speed of the motor is proportional to the input voltage V_1, then, since the motor drives the slidewire contactor,

$$\frac{dV_o}{dt} = -KV_1$$

where K is a positive constant. Applying Kirchhoff's Law of currents to junction A gives

$$-I + \frac{CdV_1}{dt} + \frac{V_1 - V_o}{R} + \frac{C_1 d(V_1 - V_o)}{dt} = 0$$

which simplifies to

$$\frac{d^2V_o}{dt^2} + \frac{1}{C + C_1}\left(\frac{1}{R} + KC_1\right)\frac{dV_o}{dt} + \frac{K}{R(C + C_1)}V_o = \frac{-KI}{C + C_1}$$

where V_o is the feedback voltage and indicated output. If $K = 10$ (experimental value), $C = 100$ $\mu\mu$f, $R = 10^{11}$ and $C_1 = 0$, the roots of this equation are

$$S_1, S_2 = -1/20 \pm j1$$

indicating an underdamped system with a damping time constant of 20 seconds. If, however,

$$C_1 = \frac{1}{RK} + \frac{4C}{RK}$$

it can be shown that the roots will be

$$S_1 = S_2 = -1.8$$

so that the system is critically damped

* L. Stanton, *Proc. I.R.E.* **34**, 447 (1946).

with a time constant of 0.55 seconds.

The experimental values agree very well with the values computed, even though some discontinuities exist in the practical problem such as the a-c amplifier saturating and the length of the slidewire being finite. The speed of response is slower than the computed values for small input capacitances because the speed of the motor is such that it takes 4 seconds to drive the slidewire contactor the span of the recorder.

Reduction of Contact Potential

The chief cause of instability in vibrating capacitor electrometers is a variation with time of the contact potential differences of the two plates forming the vibrating capacitor. Since it is impossible at present to make two surfaces having the same work function, there is always a slight contact potential difference between the plates of any capacitor. This effect can be balanced out by means of a zero adjustment, so its existence is unimportant, but it is important that its value stay constant. It has been found that both gold and rhodium capacitor plate surfaces have excellent qualities as far as contact potential drift is concerned if they are carefully applied. For the first day or more of initial operation, the contact potential changes rapidly in an exponential manner, sometimes even changing polarity, until it settles down to some fairly constant value.

The plate is usually made from steel or brass and the surface ground. It is unnecessary to grind the surfaces optically, but it is necessary to have them sufficiently flat so they can be vibrated with very little separation and not touch. Air damping is higher if the plates are parallel so there is less tendency to touch due to shock or overvoltage on the exciting coil. If brass is used, the surface is nickel-plated to guard against the copper atoms migrating through the rare-metal surface. This is simply a precaution, however, as there is no experimental evidence that it is necessary.

For both surfaces the method of preparation is the same. The base surface of the plate is first cleaned by a strong basic solution, as is standard in plating practice, and gold or rhodium plated with about 0.0005 of an inch layer of metal. The surface is then burnished with a burnishing tool, cleaned again, and then plated with about a 0.0001 of an inch of the metal being used. Before final assembly, the surface is cleaned with petroleum ether followed by methanol. Considerable work was done in preparing plates by optically grinding the capacitor plates flat, gold plating, and then evaporating gold on this surface. However, the method described gave better and more uniform results. It has been found that gold plates will drift somewhat with temperature but will usually stay within a band of approximately ½ mv for a period of months. Diurnal variations are about 0.2 mv with temperature variations of the order of 20 to 25° F.

In preliminary tests, rhodium has shown less variation than gold, but the testing has not yet been sufficient to give conclusive results. It is thought that rhodium should give the best results when the surfaces are properly prepared, because the variations of work function for this metal as reported in the literature are smaller than for any other metal. The thermionic and photoelectric work functions are also in excellent agreement. The chamber containing the vibrating capacitor has been made air-tight for the purpose of admitting rare gasses in an effort to reduce the contact potential drift. However, it was found that after evacuating the chamber, admitting argon gas, reevacuating, admitting argon gas and sealing, contact potential drift agreed with that in air.

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Vacuum Tubes

The first stage of amplification is critical in electrometers. In this electrometer the first amplifier tube is a 6AK5. The filament is operated at about 4½ volts d-c with a plate voltage of about 35 volts. D-C is necessary for the filaments of the first two stages because of excessive a-c introduced through the heater-to-cathode capacitance by the filament voltage. Low heater voltage also tends to make the input impedance high enough to provide good sensitivity, but low enough to be obtainable with standard tubes. 10^{10} ohms is sufficient. A lower impedance than this will lower the sensitivity but will not affect the position of the null balance. Thus, the tube performance is not nearly as critical as in a d-c electrometer input tube.

The second stage is a cathode follower which serves to step down the high output impedance of the first stage to a low impedance which will more nearly match the low input impedance of the a-c amplifier. This stage is also operated at a reduced filament voltage as well as low plate current in an effort to increase tube life. It is desirable that the preamplifier operate for at least a year without requiring maintenance, so that it can be used untended in a radioactive area with an ionization chamber.

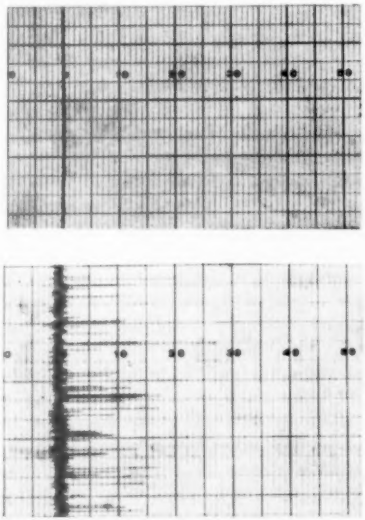

Fig. 5. Two sections of chart paper; (above) with input shorted, (below) with an alpha source in an attached ionization chamber

Insulation

The input impedance depends on the input resistor and the insulation of the input circuit to ground including leakage through the vibrating capacitor. All insulators in the input section of the preamplifier are made of Teflon, and the vibrating capacitor has an air dielectric. Surface leakage is kept low by keeping the preamplifier dry. This is accomplished by having the filaments of the two tubes in the preamplifier on continuously.

PERFORMANCE

In Fig. 5 are shown two sections of chart paper representing about 1 hour in time taken from the electrometers. Shown above is a trace with the input shorted. This recorded value then depends on noise and contact potential drift. Below is a trace with an ionization chamber attached and with an alpha source in the ionization chamber. The time required to trace one of the larger spikes is about 4 seconds. The ionization chamber is directly on top of the preamplifier.

For both traces full-scale (100) represents 10^{-13} amperes or 10 millivolts, the input resistor being 10^{11} ohms.

A number of these electrometers have been made, and it has been found that it is quite easy to get reproducible results. The instruments have been uniform in sensitivity, drift, speed of response, *etc.* One unit used periodically for a year has had no component failures. —END

Engineering Aspetcs of Nuclear Reactors — IV

Nuclear power plants are considered here as a whole. Application of pile heat to gas turbines, ramjets and rockets is discussed in relation to the whole system. Limitation on use of nuclear energy because of fuel scarcity is also detailed.

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THE RELATIONSHIP OF the pile to the other components of any power system is that it merely replaces the source of heat in the system. The heat produced must be removed continuously or intermittently for dissipation as a waste product or for conversion to useful form. The dissipation of waste heat from piles utilized as research units or as isotope producers is generally simpler to achieve mechanically than the conversion of this heat to useful form. Nevertheless, the complete system for handling the pile heat removal and disposition may be quite similar and even equally complex in both cases. Therefore, we will consider the general engineering arrangements of the components in any nuclear-powered plant or system and the operating characteristics of the plant as a whole.

In all nuclear power plant systems, the designer is faced with the problem of possible contamination of various components of the power plant by radioactivity. This precludes normal servicing and maintenance. In some systems, this may not be serious, or it may be possible to guarantee full protection against contamination of the cooling stream by fission recoils or the radioactive products of corrosion or erosion. When such protection is possible, a single or unitary system of heat absorption and disposition is by far the most desirable. Here, the coolant for the pile carries the heat directly to the point of dissipation or conversion to useful energy.

However, when it is impossible to guarantee a complete lack of contamination in the pile coolant, and this contamination would be undesirable in other parts of the equipment, then a binary system must be used. Here, the heat is removed from the pile in either an open or closed cycle system and is transferred by means of a heat exchanger to a second system which may also be either a closed or open cycle system. The heat is then conveyed to its point of application or conversion to other forms of useful power. In this way, the entire secondary system is kept free of contamination, and, hence, can be serviced and maintained at will. Only the heat exchanger and the primary cooling system will be contaminated by any radioactivity and will therefore be unapproachable, except under special conditions.

The arrangement of the cooling system for the pile depends upon a number of factors, such as economy, material availability and abundance, the plant purpose, the operating conditions and limitations, the type of coolant chosen, *etc.* Obviously, the simplest arrangement is an open cycle or once-through

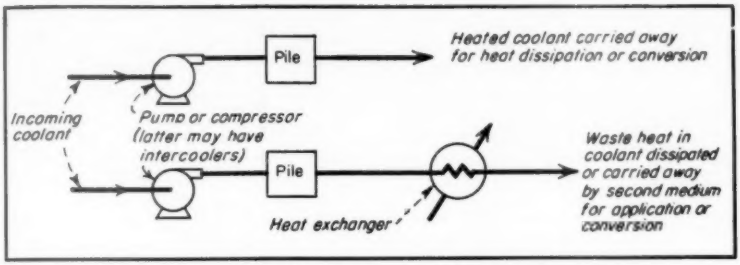
Pile
Heated coolant carried away for heat dissipation or conversion
Incoming coolant
Pump or compressor (latter may have intercoolers)
Pile
Waste heat in coolant dissipated or carried away by second medium for application or conversion
Heat exchanger

FIG. 1. Open-cycle unitary (above) and binary (below) systems

type of cooling system. In this, the coolant enters the pile, picks up heat, carries it to the point of application or disposal, and is then thrown away, as indicated in Fig. 1. Of course, the open cycle system is generally practical only with a plentiful and inexpensive coolant like air or water, except in the case of a rocket drive.

When air is used as the coolant in an open cycle system, most power systems do not require any pretreatment of the air before it is pumped into the pile. However, in special cases (usually for stationary power plant application), it may be necessary to filter and/or dry the air before pumping it through the pile to obtain the best over-all performance. In other cases (usually in mobile power plants), it may be necessary to expand and reduce the pressure of the air before pumping it through the pile.

Once heated by the pile, the air may lose its heat by dispersion to the atmosphere, provided all parts of the pile are properly protected to prevent the escape of fission fragments or the radioactive products of corrosion or erosion. If the heat is to be wasted and it is impossible to prevent the contamination of the coolant air stream, then the air must be disposed of through a very high stack or other means to eliminate hazards to the personnel and equipment in the vicinity.

If the heat in the air is to be usefully employed, it can be passed through a

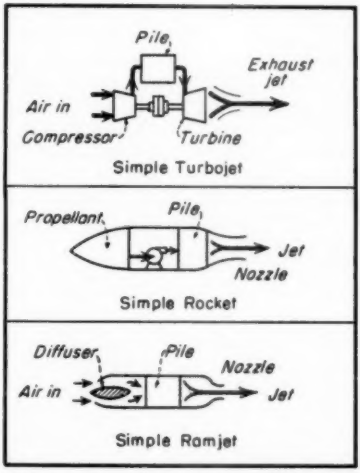

FIG. 2 Examples of open-cycle systems

space heating system, an air turbine or other means suitable for utilizing or converting the heat in the air before it is discharged. However, if the air from the pile is contaminated, it cannot be used directly in a space heating system because of the radiation hazard, nor will it be useful in an air turbine or other power converter using the air directly unless the machine can be operated for long periods without servicing or maintenance.

Of course, this radioactive contamination of the operating equipment can be avoided by use of a binary system, in

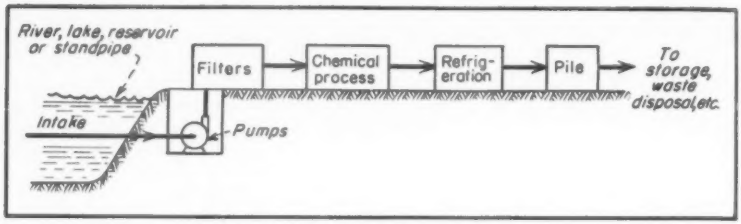

Fig. 3. Open-cycle water-cooled system

which the air for cooling the pile operates in an open cycle. Since only heat and none of the radioactivity would be transferred by the heat exchanger, the coolant, the mechanical equipment, and all parts of the secondary system except the heat exchanger would be completely free of any contained radiation hazards. Air-operated simple turbojets, ram jets, and rockets, such as will be described later, are typical examples of open cycle systems for nuclear power plants. See Fig. 2.

If water is used as the coolant in an open-cycle system, it may be necessary to pretreat and purify the water before using it in the pile by chemically processing it, filtering it, or treating it by other suitable means. In some cases, it may even be necessary to precool the water before using it in the reactor. Therefore, an open-cycle water-cooled system might be as shown in Fig. 3 (except that any of the processes can be omitted in a particular application).

If the heat is to be wasted, the water may be allowed to run into any convenient waste disposal facility (such as a nearby river) if there is no contamination present. However, if contamination exists, the disposal of the water presents a different problem which depends upon the intensity and density of the radioactivity contained therein. In some cases it might be possible to dispose of this contaminated water by pumping it into a large river with a high flow rate so that the dilution of the contaminated water by the fresh water will reduce any radiation hazards downstream to a safe, permissible limit.

Alternatively, the contaminated water might be pumped well out into a large lake and discharged far below the surface so that it would be dispersed and diluted. Of course, both of these methods must also take into account the long range and short term effects on marine flora and fauna close to the point of discharge.

If conditions do not permit disposal by dilution, contaminated water from

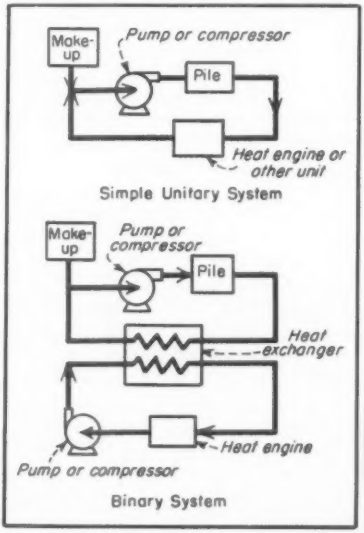

FIG. 4. Closed-cycle unitary and binary systems. In the latter, an open-cycle secondary system could be substituted for the closed-cycle secondary illustrated

an open-cycle system has to be stored in large reservoirs suitably located and shielded. After the radioactivity in the water decays to a safe level, this impounded water can be discharged to natural run-off areas, rivers or lakes. Even though the water from the pile were not normally contaminated, temporary storage basins between the pile and the ultimate disposal point might still be a safeguard against an accident in which the water would become contaminated.

When the coolant is one that cannot be wasted (such as gases like helium or CO_2, liquids like heavy water, or solids like the molten metals or salts), the cooling arrangement through the pile must be made in the form of a closed-cycle system as indicated in Fig. 4.

The mechanical equipment for utilizing the heat or converting it to useful power in any of the above open or closed cycles and unitary or binary systems is of the conventional type and will not be described here. However, some applications of the open or closed unitary or binary systems are a trifle less conventional and warrant a more detailed description.

Nuclear-powered Gas Turbines

The heat from a nuclear reactor may be substituted either directly or indirectly for that normally produced by the combustion chamber of a gas turbine. In this way, turbojets and turboprops can be operated by a pile, with all the advantages of the high performance attained by piles. As in the case of other nuclear power plants, the gas turbine system can be arranged either

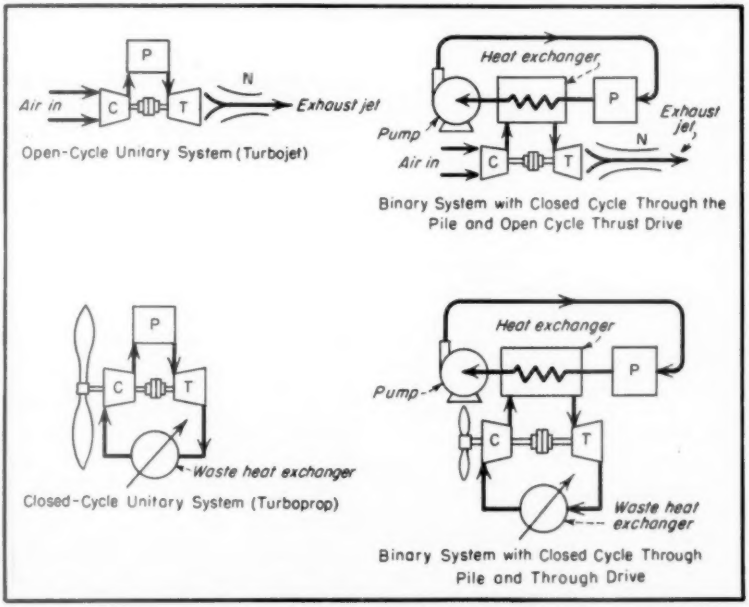

FIG. 5. Nuclear-powered gas turbine arrangements. Either axial or centrifugal compressors are indicated by a C; turbines by T; the pile by P; and exhaust nozzles by N

as an open or a closed unitary or binary system, as indicated in Fig. 5.

Let us consider only the simplest of these, the open-cycle unitary system. In a turbojet, for example, the nozzle and jet normally are located at the downstream end of the set of four simple components in the system. However, there are a number of permutations and arrangements of the compressor, turbine, and pile units in a turbojet. Since the compressor and turbine may be single units or may be multiple units or may even be a common unit having the turbine on the outside of the compressor wheel, or vice versa, many design combinations are possible. Figure 6 shows a few of these arrangements.

Any single combination of the four basic components of a turbojet may have further variations according to the pattern of the gas paths through the system. In some cases, there may even be intermediate heat exchangers for reasons of structural necessity or heat economy.

The most compact of all the possible arrangements of a simple, open-cycle turbojet is obviously the one in which the pile is located between the compressor and the turbine with a straight through gas path. Such an arrangement would normally have the least frontal area with the most direct gas flow and the shortest hot and cold gas passages. However, the drive shaft between the compressor and turbine cannot go through the pile as in Fig. 7 unless it is made of a material having a very low neutron capture cross section. Unfortunately, there are few, if any, materials that will stand the stresses at the operating temperature and still be transparent to neutrons. Therefore, this arrangement generally requires multiple drive shafts outside the pile, somewhat like a planetary system. This increases the frontal area, which may or may not be objectionable. If it is not objectionable, the use of combination or multiple turbine or compressor units may prove more advantageous in some cases.

Since the pile produces heat, its materials are hotter than the gas stream through it, while the turbine which uses the heat in the gas is cooler than this same gas stream. Nevertheless,

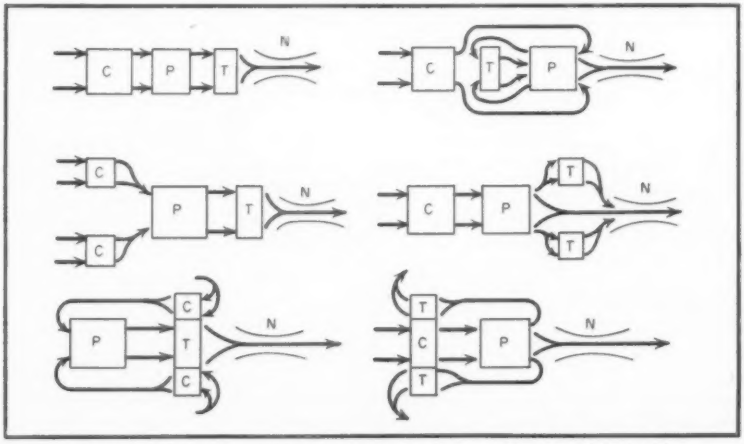

FIG. 6. Various component arrangements for a pile-heated turbojet

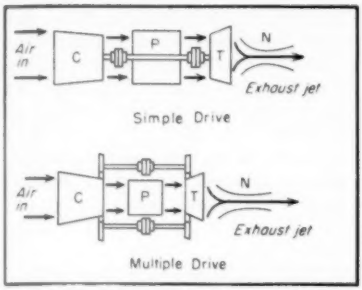

FIG. 7. Open-cycle unitary turbojet

the turbine rotates and the pile is stationary, so that the stresses and limitations in the materials of construction of the turbine usually limit the top operating temperature of the gas through the turbine to a level lower than that through the pile.

To take advantage of the higher operating temperature in the pile without endangering the turbine and without sacrificing any of the energy transmitted to the jet, several arrangements are possible. Some of these are indicated in Fig. 8 which shows (1) cool gas bypassing the pile to moderate the gas through the turbine, (2) cool gas bypassing both the pile and the turbine but picking up some of the pile heat in an exchanger and carrying it to the thrust jet, (3) jet augmentation by means of an exchanger, and (4) most of the pile-heated gas going directly to the jet with only enough bypass through the turbine to drive the compressor.

The last arrangement indicates a principle that might be incorporated into other designs—that of splitting the flow of coolant through the pile so that the flow through the cooler section of the pile carries out only enough pile-produced heat to operate the turbine while the balance of the pile's energy is carried directly into the thrust jet. Even the exhaust gases from the turbine might be recycled through the

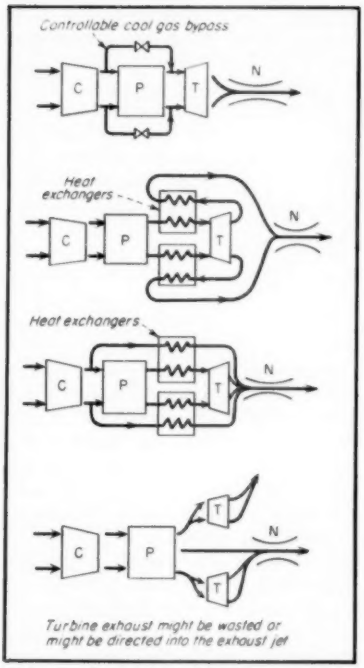

FIG. 8. Examples of turbine temperature reduction or control

pile again to pick up more heat before being discharged through the jet nozzle. Piles built into the rotor of one of the gas turbine elements and hollow drive shafts for the insertion of controls and the cooling of inaccessible bearings in hot regions of the gas turbine are other possible variations in mechanical details.

With all the variations indicated above in the number and arrangement of the various components and gas paths, in the auxiliary bypasses and heat exchangers, and in the mechanical details, it can be seen that there are innumerable possibilities in the design of pile-heated gas turbine units, and each must be a custom-built job tailored to the needs and specifications of its use. In general, however, there are certain fundamental factors that must

inevitably govern the choice of final design. These include the problem of cooling the bearings and other important moving parts, limiting the path of the hottest gases to conserve heat and reduce structural problems, limiting the top operating temperature for the materials of construction in the turbine, limitations on space and frontal area, the method of applying the power developed by the gas turbine (by means of an open or ducted air screw, a jet, or both), *etc.*

Whereas all of the foregoing discussion has been directed toward the open-cycle unitary gas turbine, many of the variable factors described are applicable to the other systems shown in Fig. 5. However, the closed-cycle unitary system cannot be used for a turbojet but only for a mechanical drive such as a turboprop. The simple closed-cycle unitary system might be operated with either steam or mercury using a steam or mercury turbine as the drive unit, a condenser as the waste heat exchanger, and a liquid pump in place of the compressor shown in the diagram. Helium and carbon dioxide are other possible coolants for the closed-cycle unitary system. However, steam and carbon dioxide in a closed cycle are objectionable because of the molecular decomposition caused by the neutron irradiation in the pile. A single pass through the pile might not cause much decomposition, but the continued recycling of these vapors or gases would cause an accumulation of decomposition products that could be serious. Certainly, some replacement from makeup storage and regeneration or proper disposal of the coolant components will be needed.

In the binary system, the closed cycle through the pile might employ steam, mercury, helium, carbon dioxide, molten metals, or any suitable coolant that can be operated in a closed cycle. The open cycle through the turbojet would obviously use air, while the closed cycle through the turboprop would have to use some gas or vapor suitable for driving a turbine. In the binary system, it is also possible to arrange for the turbine in the gas turbine unit to drive not only the compressor in its unit, but the pump or compressor in the other section of the binary system.

Control of Nuclear-powered Gas Turbines

The nuclear reactor itself, in a nuclear-powered gas turbine, is controlled according to previously described principles. Incorporating the pile into a gas turbine does not change the pile controls in any way except for the possible mechanical complications of having to insert the pile controls through hollow drive shafts or around other mechanical components, *etc.* However, it must be remembered that the ultimate goal is not the control of the individual components but the over-all control of the power plant as a whole.

Gas turbines and their compressors are essentially high-speed machines that are very sensitive to changes in speed. As the speed of the compressor is decreased, the power output falls off rapidly until, at about 50% of the full rated speed, the turbine may just drive the power plant itself without any external load. As the turbine speed is increased, the gas temperature through the turbine and the power output increase, and these increases have significant effects upon the turbine itself. The increase in RPM increases the stresses in the turbine blades in proportion to the square of the speed. Also, the physical properties of the material in the turbine blades deteriorate more rapidly with increased temperature.

Since the stresses in the moving parts of the turbine (primarily the turbine blades and the turbine wheel) depend upon the speed and temperature of the turbine, these two factors must be con-

trolled very closely. Turbine materials may be operating relatively close to their elastic limits at their full rated speed, so that overspeeds or overtemperatures, even for short duration, may be very detrimental. Accordingly, the power plant control must control the maximum temperature and speed of the power plant within narrow limits and with a high degree of stability to avoid hunting and to avoid excess speed or temperature for even short periods. Likewise, the temperature and speed must be controlled with this accuracy and stability over the full range of possible operating conditions which the power plant may encounter, such as change in altitude, air temperature, or air speed.

Of course, the speed and temperature that can be tolerated in the gas turbine depend upon the materials of construction. Presently known and tested materials cannot be operated safely above about 875° C, although attempts are being made to develop materials for use at higher temperatures. Since gas turbines are not very efficient below temperatures of about 500° to 600° C, the control range is rather limited, with very definite limitations on the top temperature. Since the allowable creep stresses are a function of temperature while the actual stresses are a function of speed, it is apparent that both speed and temperature must operate the controls.

In general, therefore, the control for the gas turbine is simply a means for regulating the temperature of the gases to the turbine, with safety limit controls to prevent greater than maximum safe operating speed or temperature. While it may be possible in some cases to control the gas temperature to the turbine simply by changing the power output of the pile, this is not a very satisfactory method for a mobile power plant such as an aircraft drive because the response of a controlled pile to changes in power level is usually too sluggish for prompt reply to the power plant's demand for quick changes in power level. Therefore, while the pile power level control can be used for starting up and shutting down the power plant in general, and for large, slowly delivered changes in power level, other control methods must be employed for quick changes in power and general control.

The easiest and probably the most practical of these appears to be diluting the hot gas to the turbine with cold gas bypassed directly from the compressor, as indicated in some of the sketches in Fig. 8, with possibly the addition of a bypass to waste some of the hot gas from the pile before it reaches the turbine. With this principle, the pile is operated at approximately constant power level and the bypass used to control the power plant output. It does not matter at what power level the pile is operated because the excess energy from the pile can be wasted.

Since fuel economy is not a consideration in nuclear-powered gas turbines, such a power plant might be operated at or near its rated load, using only such power as is needed at the time and wasting the balance. For example, if the gas turbine were utilized to drive a propeller, the propeller could be a variable pitch type so that the turboprop could be operated at full speed at all times but only the desired amount of power used, depending upon the pitch of the propeller blades. As another example, turbojets might be operated at full thrust continuously (except at landing) and jet spoilers employed to cut down the useful part of the thrust as required.

The application of nuclear-powered gas turbines to turboprops introduces a number of other problems that add to the control requirements. For example, in some cases, the windmilling action of the prop might drive the power plant at speeds in excess of its maximum

permissible speed, even though the gas temperatures were relatively safe. Conversely, the windmilling might tend to reduce the speed of the shaft below that necessary for the adequate cooling of the pile at the power level at which it was operating.

After a pile has been operating for a period of time at any power level, shutting down the pile will not reduce the power output to zero but will still leave some heat to be dissipated from the pile because of the residual radioactivity contained therein. Depending upon the operating time and history, this residual heat may amount to as much as several percent of the total rated output. Since it might be enough in some cases to cause mechanical or thermal difficulties, it may be necessary to continue the operation of the power plant at reduced speeds in order to provide pile cooling that will carry away this residual heat.

If the gas turbine is a mobile power plant, the additional energy removed from the pile after shutdown must still be dissipated even though the power plant's driving force must be zero. If the drive cannot be disconnected, or if the residual heat is insufficient to operate the power plant at this reduced output, an auxiliary means must be provided. In any case, pile temperature controls will determine the operation of the cooling system.

Ramjets

At first thought, nuclear reactors might appear to be ideal heat sources for ramjets because of their relative simplicity and because of their "unlimited fuel supply." However, the characteristics of the pile and of the ramjet are rather incompatible and make this application somewhat more questionable than that of nuclear power to a gas turbine.

Ramjets are very high speed drives operating largely in the supersonic region. The high speed necessary for the efficient use of a ramjet drive raises the impact temperature in the incoming air. While this may be ideal for a combustion type of heat source, it is not too good for a nuclear heat source because it reduces the heat transfer so markedly. This means a large heat transfer surface-to-volume ratio in the pile in order to get a large power output, but the allowable pressure drop through the pile is so limited that the heat transfer area or friction surface should be small. Likewise, maximum heat transfer requires maximum air density, but this also increases the impact temperatures. These conflicting factors necessitate individual study of any specific application to determine its feasibility and practicability.

Of course, the lack of moving parts in the high temperature zone of a ramjet obviates most of the problem of high creep strength, but then a ramjet must necessarily operate at a much higher temperature than a gas turbine. Therefore, there undoubtedly will still be a materials-of-construction problem because there still will be temperature limitations imposed by some one of the components in the pile itself, whether it be the nuclear fuel, the moderator, the jacketing on the fuel, or the controls.

Functionally, the control of a ramjet is rather simple. There only need be an "on-off" control with a safety to prevent overheating the pile and one to prevent too low a velocity of the ramjet with a consequent loss of flight. However, the actual mechanical details of these controls may not be as simple as the description of their functions.

The limiting temperature control would merely have to cut the power level of the pile down in case of overheating and raise it again after the pile had cooled sufficiently, bringing it back to its original power level. To control a loss of velocity might be more diffi-

cult since it would necessitate increasing the pile power output by means of the pile control, and this might be opposed by the safety controls. General flight speed could be controlled by controlling the pile power level but, as in turbojets, it might be better to keep the power plant running at full speed almost continuously and provide jet spoilers as a means of controlling rapidly.

Since ramjets must have a speed of some few hundred miles per hour before becoming self-operative, the problem of takeoff and landing of such drives is complex. In particular, if the velocity of an aircraft driven by a ramjet were to drop below the critical speed for that drive, the ramjet could not become self-operative again without an auxiliary power booster such as a power-heated rocket or turbojet drive.

Rockets

Rockets cannot use the medium through which they travel as their propellant in the way that turbojets and ramjets do, but must carry along their own propellant. While the advantage of higher specific impulse is gained by being able to use molecular or atomic hydrogen as a propellant instead of one that must be oxidized, the idiosyncracy of having to cool a pile after shutdown in some cases might offset some of the advantage of nuclear power. Part of the propellant or a supply of auxiliary coolant would have to be retained for this after-shutdown cooling. However, short duration propulsion probably would not require after-shutdown cooling.

The very limited period during which the flight power is operative makes a simple "on-off" type of rocket almost a necessity. The "on" position would still need automatic safety controls to prevent overheating, and the "off" position might require the application of some coolant, but there would seem to be no particular advantage in being able to control the pile to intermediate power levels.

Limitations and Applications

In a review of the problems involved in the use of nuclear energy, it can be stated that the need for better sources of new nuclear fuels is one of the most significant problems. Since there are only three good nuclear fuels presently known and no more are likely to be developed within the near future, the atomic energy industry is at the mercy of a limited fuel supply. Two of these fuels must be produced artificially, while only one, U^{235}, occurs in nature.

It is recognized by the geophysicists that there are about 10^{15} tons of natural uranium in the earth's crust and 10^{10} tons in the ocean. In fact, the uranium in the earth's crust is more plentiful than many other elements with which we are familiar, such as cadmium, bismuth, silver, mercury, and iodine; and it is a thousand times as plentiful as gold. Nevertheless, in about 95% of the earth's crust, it is found in concentrations of only ¼ of an ounce per ton of ore or less.

Only in a few places on earth is uranium found in worthwhile concentrations. Here the uranium metal constitutes about one part in 50 to 500 parts of ore. Unfortunately, in these rare locations, the total amount of readily available uranium is limited and is found in limited pockets of known extent. Figures published in 1939 showed about 5,000 tons of natural uranium in Canada and the same in Belgian Congo at concentrations of one part in about 50 to 100 parts of ore, and about 5,000 tons in the U. S. and 4,000 tons in Russia and Czechoslovakia at a concentration of about one part in 250 to 500 parts of ore.

That totals about 19,000 tons of natural uranium readily available in the world, of which only about 136 tons are the fissionable isotope U^{235},

and there seems to be little likelihood of any unusual finds which would increase our supply. Therefore, the greatest effort must be directed toward the production of the two artificially produced nuclear fuels.

Obviously, since there is 140 times as much U^{238} in natural uranium as there is U^{235}, the potential supply of plutonium is much greater than that of U^{235}. Likewise, the potential supply of the other artificial fuel, U^{233}, is even greater than that of plutonium, since it is produced from thorium, which is at least three times as plentiful as uranium in the earth's crust with at least one known pocket of about 180,000 tons in British East India. Unfortunately, the greater potential supplies of the artificial fuels will be useless to us unless methods are developed of producing them at a rate greater than the original fuel is consumed in the production.

Many economic comparisons have been attempted on the cost of nuclear energy compared to that of conventional sources. Since one pound of U^{235} is the equivalent in heating value of 1,500 tons of coal, the cost of this coal is frequently used as a comparative figure for the competitive use of nuclear energy. However, there are other factors to be taken into consideration in making such a comparison.

While it is true that one pound of U^{235} can be extracted from 140 pounds of natural uranium, the consumption of one pound of U^{235} in the process of producing nuclear power requires many additional processes other than the simple extraction. The pound of U^{235} cannot be used in a pile until it is all fissioned, but can only be slightly consumed before it must be removed from the pile and reprocessed to remove the fission fragments and reclaim the unburned U^{235}. This must again be fabricated into fuel shapes and replaced into the pile for refissioning. Before the entire pound of U^{235} is consumed, it will have been reprocessed many times. Since no processing and fabricating technique is 100% efficient, there are additional losses from the frequent handling of the material. Not only these losses but the cost of reprocessing and refabricating must be considered along with the extraction of the U^{235} from natural uranium in determining the actual cost of the fuel.

Even after we consider the comparative cost of this fuel as against a common fuel like coal, we must remember that when coal is used as fuel for the production of steam-generated electricity, for example, the fuel cost is only about 20% of the total cost of the power production and distribution. Therefore, if the nuclear fuel were free, it still would result in a saving of only 20% of the total cost of the power, just as the power cost would increase by about 20% if nuclear fuel cost twice as much as coal.

We must also remember that we are comparing a limited or premium fuel with one that is quite common. Therefore, in general, there seems to be no point in trying to compete with a common fuel at the expense of one having such a limited supply.

In the case of hydroelectric sources, we are competing with a free source of energy, but again we must take into account the balance of the cost in producing and distributing this energy. Of course, it must also be remembered that electric power cannot be economically transmitted over a range greater than about 300 miles. Therefore, hydroelectric power is limited in range and location by the source of water supply.

Even though no general replacement of common sources of power, like coal and water, by a limited fuel seems practical, we might class as a premium use the production of power by nuclear energy in such locations as southern

China, Argentina, and the Mediterranean, where no coal or water power is available.

However, when we review all the types of power used by mankind, we find that only four percent of the total is produced in stationary power plants, with the remaining 96% produced in mobile units. Therefore, premium use may come in mobile power plants.

On land, there are two possible applications, railroads and automobiles. However, the massive radiation shielding required makes such application unfeasible.

In marine applications, because of its almost unlimited fuel supply and range, nuclear power can be favorably applied. Ships can be driven unlimited distances without having to refuel enroute. However, the shielding requirements are such that it is unlikely that this type of power plant could be placed on any surface craft smaller than a destroyer. Under water, nuclear power again finds a premium application because existing submarines are limited in range under water. With nuclear power, the only limitation of underwater range for a submarine would probably be the ability of the personnel to live under water for any length of time.

In the air, refuelling techniques and improved fuels have been developed to the point that combustion-powered craft can probably be flown at least half way round the earth, or can be driven at speeds in excess of the speed of sound. However, these long range units are slow-speed craft, while the high-speed units are badly limited in range by the amount of fuel that can be carried. Only with nuclear power can one achieve not only long range but high speed over that range. In combustion-powered craft designed to travel at any particular maximum speed, the range increases as the airplane gross weight increases but at a much slower rate, until finally one reaches a maximum range beyond which the craft cannot go, no matter how heavy it is made. Likewise, for any particular weight of airplane, the greater the speed for which it is designed, the shorter the range that must be accepted. With nuclear-powered craft, the range for any speed and weight of plane is practically unlimited and is simply a matter of choosing the size and speed desired.

In closing, one cannot help considering a few power comparisons. Man uses a total energy per year of about 3×10^9 kw. If all the readily available supply of uranium in the earth's crust were converted to energy for man's use, it would only last about a thousand hours. Even the readily available uranium in the United States could only supply all our power needs for a matter of months. Yet there falls upon the earth every day a source of energy 50,000 times greater than the total energy used by all mankind—the solar radiation emitted by the nuclear reactions going on in the sun.

The solar energy that falls upon the earth in only fifteen days is as great as that contained in all the coal resources in all the earth. On the other hand, it would take 30,000 years for the solar energy falling on earth to produce as much as that which can be produced from all the U^{235} in all the earth's crust. Unfortunately, neither solar nor nuclear energy can be utilized at present, and much development must occur before these competitive power sources can be properly evaluated. The main point to be observed is that solar energy is common enough to become a regular source of all commercial power on earth, while nuclear energy must remain a premium type of power for some time to come.

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This is the last of four articles in this series. The previous articles appeared in December, 1949, and January and February, 1950.

Controlling a Power-producing Nuclear Reactor*

Automatic control is a necessity if the power from a chain reaction is to be successfully harnessed. Considering basic nuclear physics, instrumentation, and servomechanisms, the author here evolves an error-rate damping control system.

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IN A NUCLEAR ENERGY power plant system, the heat developed in the reactor is the source of the power. One watt per second of power is released for every 3×10^{10} fissions per second. The heat released in fission is removed from the reactor by some sort of closed system (*1*, *2*), necessary because of the high temperatures and pressures involved.

If useful power is to be generated, the reactor must be ready to deliver upon demand. Fluctuations in reactor power or frequent shutdowns cannot be tolerated. A properly-designed automatic control system is needed.

The fact that the heat can be generated quickly is well established by the explosive nature of the atomic bomb. Also, it is evident that the reactor heat production rate could inadvertently become high enough to damage the reactor. To prevent damage a safety system is needed as a last resort. If this system operated upon the slightest provocation, the power generating value of the reactor would be lost. The control system must therefore be intelligent enough to prevent unnecessary shutdowns or at least keep these at a minimum.

Since power output is our most important consideration, the primary control signal will come from the steam cycle or load, and the neutron density will be matched to this by the control system. The neutron density, being a direct measure of the reactor power, is the most likely parameter to use for control of reactor power output.

The over-all control system then consists of two parts: a power demand signal derived from more or less standard instruments in the steam system, and a neutron-density regulating loop which matches the reactor power generated to the demand of the steam system. This latter regulatory loop is the one discussed here.

Reactor Physics

The design of any control system requires a good understanding of the process to be controlled. In the present case, a review of the essential reactor physics is necessary.

A reactor must contain fissionable nuclei and a source of neutrons in order to operate. In addition to heat generated in the fission process, one to three neutrons are released per fission. These are used to continue the reaction. Reactor power is proportional to neutron density multiplied by a constant which depends on size and the amount of fissionable material in the reactor.

Neutrons are captured by various reactor materials. It is important that more neutrons be captured in fissionable than in nonfissionable material.

* Based upon a paper presented at the AIEE Winter General Meeting, New York, N. Y., Jan. 30–Feb. 3, 1950.

Two values, k and l, serve to tell the story about neutron capture for any particular reactor. Neutrons born in fission are of high energy and must be moderated or slowed down before they will cause fission again. In a thermal reactor a neutron exists for a time l, which is about 10^{-3} seconds. During this time a neutron could have been lost to the reaction by unproductive capture or leakage. The number of neutrons retained for each fission which occurs is called k (*3*). The parameter l (*4*) is mean effective lifetime and k the effective number of neutrons produced per neutron absorbed in the reactor. Both values depend upon the reactor design. A change in k is δk such that $\delta k = k - 1$.

If $k < 1$ the pile is called subcritical; if $k > 1$, supercritical; if $k = 1$, critical. Notice that no power levels are involved. A reactor can be made critical at even very low power levels.

When $k < 1$ a multiplying medium exists in which, on the average, every l seconds each neutron present will produce k neutrons.

The source of neutrons to start things off could come from a radium-beryllium source or from spontaneous fission. An infinite chain of events results, so that after a long time the neutron population resulting from one neutron is

$$N = 1 + k + k^2 + \cdots k^{n-1}$$

This series written in closed form is

$$N = \frac{1 - k^n}{1 - k}$$

Furthermore

$$N = \frac{1}{1 - k} \; (k < 1 \text{ as } n \rightarrow \infty)$$

With $l = 10^{-3}$, n approaches ∞ in a few seconds and k^n approaches zero so long as $k \approx 0.5$, but as k approaches one, a longer and longer time is required for k^n to approach 0.

When k equals one the reactor is exactly critical, so that the neutron population rises with time as the source supplies neutrons. If the source is constant a straight-line rise in neutron population is indicated. This shows the method of determining when a reactor has been made critical.

Controlling k

Control of k in a thermal reactor is achieved by inserting movable rods of boron steel or cadmium whose net effect on the reactor is to change the reactor size (*5*). The rods can be thought of as neutron absorbers which act in such a way that the total neutron population in the reactor is reduced as they are inserted or increased as they are withdrawn. Therefore, when the rods are inserted, the active section is small; when they are removed the active section is increased.

The way to bring a reactor to critical size is as follows: At the start, enough control rod material is inserted into the reactor to keep it definitely subcritical. As the control rods are withdrawn, the subcritical formula given previously applies. If enough time is allowed for the neutron density to level off for each rod position for which the k value is less than one, a series of curves rising rather steeply at first and then leveling off could be plotted for neutron density, the leveling off occurring at higher neutron density and after greater and greater times as k approaches one. If care is taken in making small k changes by this process, a point is reached in rod setting where the curve no longer levels off but increases at a fixed rate indefinitely. This can be understood from the subcritical formula. Since k equals one the multiplication would be infinite, but would require infinite time.

The supercritical condition, in which a large multiplication in neutron density can be attained because the reactor will follow a rising exponential, occurs with $k > 1$. The rate of increase in neutron population equals the number of neu-

trons present multiplied by the rate of production of excess neutrons—those which are in excess of the number required to sustain a constant population. This excess production is just $\delta k/l$, and if there were no delayed neutrons the equation would be

$$\frac{dn}{dt} = \frac{\delta k}{l} n$$

or

$$n_{(t)} = n_0 e^{\frac{\delta k}{l} t}$$

where n_0 represents the number of neutrons present at time zero. Without a source the process could not start, and n_0 is the number of neutrons which resulted from the source. However, 0.7% of the total neutrons in a nuclear reactor are born late or are emitted at various times after fission has occurred. When these are taken into account, terms representing delays are added to the above expression, and the kinetics equations of the reactor become

$$\frac{dn}{dt} = \frac{\delta k}{l} n - \frac{\beta}{l} n + \frac{C}{\tau} \qquad (1)$$

$$\frac{dC}{dt} = \frac{\beta}{l} n - \frac{C}{\tau} \qquad (2)$$

where n = neutron density, $\delta k = k - 1$, β = fraction of total neutrons delayed 0.007 (4), l = mean effective neutron lifetime, C = concentration of delayed neutron emitters, and τ = average decay period of delay emitter = 10 sec.

These equations are written from the physical fact that the rate of neutron density change is equal to the excess neutrons produced per neutron absorbed in fission per neutron lifetime, times the number of neutrons present per unit volume. This total production is represented by the first term of Eq. 1. The fact that 0.007 of the total neutrons are not emitted immediately when fission occurs is reflected in the second term, which consists of the fraction of total delayed neutrons per fission times the number of neutrons present divided by the mean effective time between fissions. The third term reflects the rate of formation of these delayed neutrons, and consists of the concentration of delayed emitter divided by the emitter decay period.

Equation 2 shows that the delayed emitter concentration changes at a rate equal to its rate of formation less its rate of decay, the terms being the same as those in Eq. 1.

The picture is simplified here by use of an average group of delays to represent the several delay groups which actually exist.

To solve these equations we assume that dn/dt and dC/dt equal zero at time zero, and that the solution for a step change δk is a sum of exponentials of the form

$$n(t) = Ae^{\alpha_1 t} + Be^{\alpha_2 t}$$

For varying magnitudes of a step δk, the transient curves of Fig. 1 are generated. These curves, especially the curve showing a δk of 0.003, might be described by a single positive exponent if we are willing to ignore the effect of delays. It is interesting to note the difference in the situation as a result of the delays.

If delayed neutrons were not present the equation would be

$$\frac{dn}{dt} = \frac{\delta k}{l} n = \frac{0.003}{0.001} n = 3n$$

$$\frac{n(t)}{n_0} = e^{3t}$$

From the curves in Fig. 1, $n(t)/n_0 \approx 6$ at $t = 10$ sec. Using this ratio in the latter formula,

$$6 = e^{3t}$$

$$\frac{\log 6}{3} = t$$

$$t = \frac{1.79}{3} = 0.59 \text{ sec}$$

The delays have made the control problem much easier by increasing the reactor period. This is what is usually referred to as "control by delayed

neutrons." Assuming now that, by the previously described method, the reactor has been brought to critical, advantage can be taken of this positive period by withdrawing enough control rod material to make the reactor supercritical. The neutron density follows a rise curve corresponding to the δk provided and in time will become very high.

To get an order of magnitude into the picture, let an experimental reactor be critical at a neutron density of 100 neutrons per cm³. Power might be generated with a neutron density of 10^8 neutrons/cm³. This multiplication of 6 powers of 10 can take place in a short time if the positive period is made short by making δk large. When the operating neutron density is reached at which power can be generated, the k must be returned to one.

$k = 1$ is recognized as that point at which the change in the density of neutrons is zero. At operating power, the change in neutron density is controlled to zero and is held in this condition by either inserting or removing small amounts of δk, through movement of the regulating rod.

With large δk the rapid increase in neutron density can generate heat faster than the rate at which heat can be removed by the coolant. This might damage the reactor or become a hazard

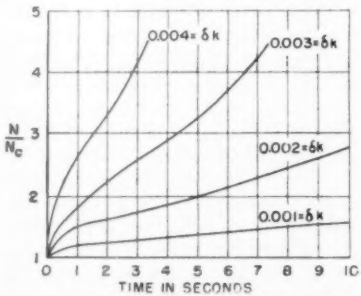

FIG. 1. Transient response of a nuclear reactor to a step change of δk

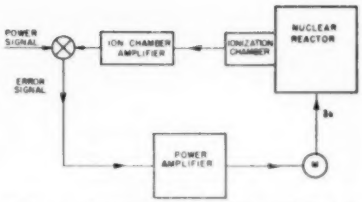

FIG. 2. Error-signal control system for a nuclear reactor

to operating personnel. To prevent any such condition, a safety-rod system can be used. These rods are always triggered and ready to be inserted if conditions warrant, thus reducing the neutron population to some safe value.

Going back to power production, we see that if the neutron density regulating system were not capable of close regulation, the safety rod mechanism might be inserted at very inconvenient times. The duty of an automatic control system for a power reactor is to hold the neutron density changes and magnitudes within safe limits and to prevent the operation of the safety system except in extreme cases.

Control System

The fundamental loop of neutron density control is shown in Fig. 2. A signal is received from the power system. This signal can be generated by standard steam-system control instruments. The reactor neutron density is measured by an ion chamber which gives off a continuous electric current in response to the number of neutrons entering it. This current is measured and compared to the power signal, the difference signal being amplified and fed to a motor which moves the control rods. Anyone familiar with automatic control immediately recognizes the importance of the ionization chamber in this control loop. Actually, the reading of the ionization chamber is controlled by changing reactor neutron density. It is assumed that the ioniza-

tion chamber is measuring the neutron density accurately.

Automatic control is dependent upon the speed of instrumentation or instrument period. Since the instrument, which indicates the condition of the process, is an important consideration in control, a short description of chamber operation is indicated.

A neutron is a neutral particle and must be detected by secondary effects. Thermal neutrons are readily absorbed by boron, so boron-coated plates or a gas containing boron is used in the ion chamber (*5*). When a neutron is absorbed by the boron, an alpha particle is given off, ionizing the chamber gas. As a result an electric current passes through the chamber.

Absorption of neutrons by boron is inversely proportional to the neutron velocity. This means that the neutron energy would affect the current flow of a chamber. This effect must be considered in ion-chamber design, but to understand the net effect on control, neutrons at only one energy need be considered.

When very few neutrons per unit volume are present in the reactor, few neutrons will enter the ion chamber per second. If the number is very low, as is the case when $k < 1$, the electric current output is a series of pulses rather than a continuous flow (*5*). The number of neutrons striking a chamber per second would vary due to statistical fluctuation, even if the average neutron density in the reactor were constant. This means that we must count pulses for a long time to get a good average value. The instrument period is therefore long at low neutron density. As the neutron density increases, the measurement time can be shortened, giving shorter and shorter instrument periods until the pulses are continuous. At this point the electric current flow can be used as a continuous measure of neutron density in the reactor.

From this point on, the instrument period is a function of the external circuit used to make the current measurement. This current is usually passed through a resistor, giving a voltage which is fed to an electronic amplifier. This resistance value multiplied by the ion chamber capacitance is the approximate period of the instrument for the neutron density measurement.

In reactor practice, there is an additional consideration. The gamma rays from the reactor structure ionize the chamber gas in the same way as the alphas from neutron capture in boron. If the number of gammas passing through a chamber per unit time is high compared to the number of neutrons, it is necessary to use two chambers, one sensitive to gammas and one sensitive to both neutrons and gammas. The difference in currents is then a measure of the neutron density itself.

The gammas are important at low neutron densities above the counting range. As the density of neutrons reaches a value at which power is produced, the gamma density is low by comparison to the neutron density and this compensation can be disregarded. Our control problem, therefore, is less severe at power level than when we are bringing a reactor up to it.

An order of magnitude for chamber current would be a useful concept at this point. For every cm^2 of ion-chamber surface, a current of about 5×10^{-10} amp flows for a thermal neutron density of 100 neutrons per cm^3. This current flowing through a 10-megohm resistor gives 5 millivolts per cm^2 of chamber surface. Therefore, one way to get shorter instrumentation periods is to increase the chamber area, thus increasing the electric current and reducing the resistor size. This is done within limits, although many factors, such as allowable physical dimensions, restrict this practice for the power reactor.

Another instrumentation considera-

tion is material depletion. As the boron captures neutrons the amount of boron decreases. This occurs in the usual exponential time relation

$$\frac{\text{Number of boron atoms present}}{\text{Original number of boron atoms}} = e^{-nv\sigma_B t}$$

where n is the neutron density in the vicinity of the chamber, v the neutron velocity, σ_B the target area of the boron atom for neutrons of velocity v, and t is time.

In time the amount of boron will be reduced a good deal, making the chamber insensitive. The quantity of original boron used is limited by the ability of alphas to penetrate the boron coat. This places a limit on the thickness of the coating. To cope with this effect, either replace the chamber frequently or keep it in relatively low neutron densities. Mentioned previously was the fact that a power reactor will probably be enclosed in a pressurized chamber, making instrument replacement inconvenient, and the fact that low neutron density means larger instrument periods was just shown.

The design factors which the control-instrument engineer faces are: ruggedness, material depletion, size, and instrument period. He must compromise for the best over-all effect and evaluate the importance of each characteristic in the particular application. Like all good designers he needs a fail-safe feature and will probably not be content with only one instrument which could fail and put the reactor out of service.

Instrument requirements having been indicated, the neutron density control loop can be discussed. A detailed discussion of servo design techniques as applied to reactors will not be undertaken. The similarity between this control loop (Fig. 2) and a servo is easily recognized. The error signal is the difference between the desired

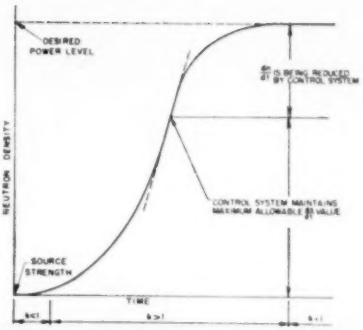

FIG. 3. Attainment of desired power level by nuclear reactor under control system

power and the reactor power. The k-changing drive is made to respond in a desirable way to this error signal so that it makes the error signal zero. When a steady level of neutron density is maintained, the error should be zero. However, a fully automatic system should safely bring the reactor to power in the shortest possible time and hold it there, in order to meet the previously mentioned requirements of power production. To bring the reactor from subcritical to power, the control system should be maintaining a positive rate of change in neutron density such that heat is not generated too quickly or too slowly at any time. The control value for this condition can be a particular voltage which represents a safe dn/dt. The control rods can be moved out of the reactor at a rate which keeps the dn/dt of the reactor at a value equal to or less than this control rate. To visualize this process as a function of time, we can draw the curve of Fig. 3.

The maximum dn/dt value is determined by the heat exchange rate possible in the reactor. The value of dn/dt above this point is proportional to the difference between the final power and the reactor power. The rate of movement of the rods and the direction in which they move are governed by the

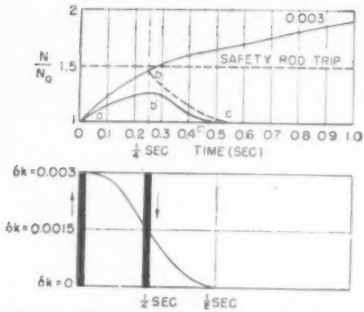

FIG. 4. Nuclear reactor transient curves showing how a step change in δk is removed by a well-designed control system

difference between the power desired and the power at any time, and by the rate of change of this difference. This is error-rate damping in servo terminology. It is interesting to note the effect of delayed neutrons at this point.

Assume that the neutron density is increasing with a 10-second period. This means that

$$\frac{n}{n_0} = e^{\frac{t}{10}}$$

Starting with a density of one, to attain a power density of 10^8,

$$10^8 = e^{\frac{t}{10}}$$
$$t = 80 \log_e 10$$
$$= 184 \text{ sec or about 3 min}$$

With allowance for tapering off or longer periods as the desired power level is approached, this time might be increased to 5 minutes. This is rather indicative of the power-producing potentialities (*4*). The delayed neutrons are following right along, and, since their average period is 10 seconds, they are not far behind at any time. If the period is increased as power level is reached, the delays will catch up; at power level there are only a few which have not arrived. In servo terminology this small delay has the effect of a small amount of integral control and will assure reaching the goal as the delays come into the picture.

For a final look at the control system, examine the power range control. Now, changes of, say, 10^3 in power are involved. This means that at 1/1,000 of full reactor power an insignificant amount of power is obtained which is materially zero. With the same 10-second period already mentioned this power change can be made in about 1 minute. Here, again, the problem seems easy to solve. However, it is not so easily defined. When the reactor is at full power, heat removal is taking place at nearly a maximum. Excursions above this power level could be dangerous and must be limited to safe values.

Control Rod Drive

A full discussion of power control cannot be undertaken here, but the following presentation is an attempt to transform the transients into the power requirements of a rod drive mechanism which will hold the reactor power close to the desired level.

Refer to Fig. 4. For the sake of this explanation assume that 1.5 times full power is the point at which we will trip the safety system, and that an inadvertent positive δk of 0.003 is instantaneously injected into the reactor causing the transient we have seen before. In the first second this transient has the shape shown in the figure. The power of the reactor will trip the safety rods in $\frac{3}{8}$ second as shown. The problem is to control the reactor below this point. If enough control rod is instantaneously inserted to equal a δk of 0.003 at $\frac{1}{4}$ second, the reactor power would follow the curve *a-b-c* and return to 100% power in about $\frac{3}{4}$ second.

Inserting step values is not practical. Compromise for simplicity of analysis on a sine function of δk as shown in the lower curve. Since large error is available immediately after $t = 0$, the

acceleration will be a maximum and the velocity represented by the slope of this δk-vs-time curve begins to increase, reaching a maximum at $t = \frac{1}{4}$ second. The rod must stop again at $\delta k = 0$, so slowing down takes place and $\delta k = 0$ occurs at $\frac{1}{2}$ second. This curve of δk is $\frac{1}{2}$ cycle of a sine curve whose amplitude is $\delta k = 0.0015$. The curve $a-b'-c'$ now represents the sort of power curve obtained if this δk correction were accomplished. (These curves were sketched to show the idea behind the control system specification and do not represent any actual case accurately.) For arbitrarily selected values of a 100-lb rod to be moved 2 feet to supply this corrective $\delta k = 0.0015$, the power required to drive the control system can be calculated:

$$\text{rod displacement} = 2 \text{ ft} \sin \omega t$$

Since $\frac{1}{2}$ cycle occurs in $\frac{1}{2}$ second, frequency = 1 cycle/sec and $\omega = 2\pi$ rad/sec, and

$$\text{rod displacement} = 2 \text{ ft} \sin 2\pi t$$

From this, the maximum velocity of 4π ft/sec and maximum acceleration of $8\pi^2$ ft/sec^2 are easily obtained. For the sine-wave motion,

$$\text{Motor H.P.} = \frac{\text{Maximum force} \times \text{Maximum velocity}}{2 \times 550}$$

$$= \frac{1}{1100} \times \frac{100}{32.2} \times 8\pi^2 \times 4\pi = 2.75 \text{ H.P.}$$

This value of horsepower is no small amount when one considers the usual range of servomechanisms. In reviewing the design parameters it is clear that lesser motor horsepower can be specified by giving due consideration to the following:

1. Make the rod lighter.
2. Make the stroke less, which means a more absorbent rod.
3. Make the allowable reactor power excursion greater, thus reducing the frequency response requirement of the control system.

A final control factor to be considered is fissionable material depletion. As fission occurs, the fertile material in the nuclear reactor is reduced. For power production the depletion of material will be rapid by comparison to the lower-power experimental reactors. The depletion amounts to a change in k of the active portion of the reactor. As a result the reactor size must be increased as time passes to keep k at 1. This effect is so much slower than the δk changes just mentioned in connection with power-level control that it is reasonable to expect that any control system designed to accomplish power regulation can be used to offset these slow changes in k due to depletion.

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2. "The Science and Engineering of Nuclear Power," edited by Clark Goodman, vol. 1, p. 196 (Addison-Wesley Press, Inc., Cambridge, Mass., 1947)
3. *Ibid*, vol. 1, p. 113
4. *Ibid*, vol. 2, chapter 8 (Note l as used $\approx l_0$ by H. Soodak.)
5. *Ibid*, vol. 1, 273

THERE is no reason to consider the use of radioactive materials or of atomic energy for peacetime uses as any more dangerous than any other type of manufacturing.

—*From an abstract of a paper by F. A. Bryan,* Ind. Med. **17,** *367 (1948)*

CROSS SECTIONS

A Sealer and Cutter for Plastic Tubing*

In "hot" radiochemical work, equipment disassembly poses a considerable problem. The tubing generally used to connect reaction and storage vessels must be resistant to caustic, acid, some organic solvents, and also be non-absorptive. At present Tygon† and Saran‡ are used extensively. After completion of chemical processes, as many lines as possible are rinsed with a decontaminant in an attempt to remove residual activity from the setup. In many instances, lines going to storage vessels and receivers cannot be rinsed because the decontaminant would dilute the final solution.

It would be undesirable to pull off or cut lines to such vessels because of the possibility of dripping radioactive solutions. The radiation intensity resulting from droplets remaining in the tube may require that this disconnecting operation be performed from a distance.

The tube sealer described here has been devised to fill the need for an instrument to separate a plastic tube from a vessel safely.

General Description

The original requirements of design were:

1. The device must seal the tubing before cutting it; and the cut must be made in the center of the sealed part, so that each of the resulting pieces is sealed at the cut.
2. The device must be operable by one person.
3. The operating head must be sufficiently light to be supported comfortably at the end of a 3-foot shaft by the operator.
4. The time of operation (sealing and cutting) should be 2 minutes or less.

These conditions were met by the following design details, as illustrated in Fig. 1 and described below:

The unit consists of a fixed jaw *C* and a movable jaw *E*, both electrically heated and mounted at one end of a 3-foot-long tube. At the other end is a suitable handle arrangement.

In operation, support tube *I* is placed under the right armpit; forward handle *J* is held with the left hand; and adjusting wheel *H* is turned with the right hand. The unit is then placed so that the tubing to be cut is between the jaws. The 110-volt power line *G* is energized while the head *E* is screwed toward head *C* by rotation of adjusting wheel *H*.

When movable head *E* has been screwed in until the tubing is fully compressed, a specific time interval (depending on size and type of tubing) is permitted to elapse before the power to the heaters is turned off and the jaws opened. Several trial seals will familiarize the operator with the correct pressure necessary for perfect sealing.

All major structural parts except the heater blocks are of aluminum. Both heater blocks are designed to supply sufficient heat to the plastic tubing to permit rapid sealing under pressure.

The distance from the supporting

* From a report (BNL-28-T-12) by Gerald J. Selvin, Brookhaven National Laboratory, Upton, N. Y.

† U. S. Stoneware Corp.

‡ Commercial Plastics Co., Dow Chemical Corp., etc.

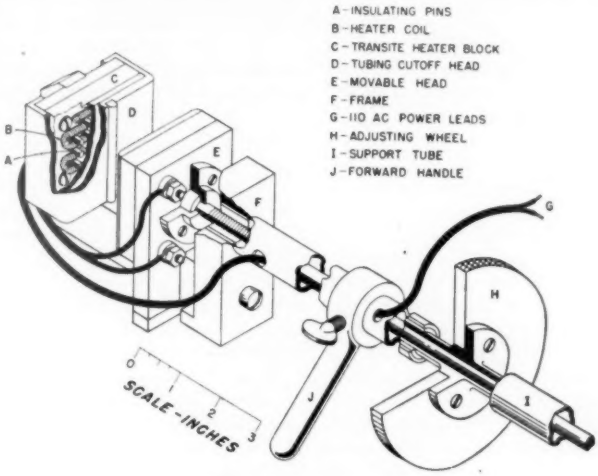

A - INSULATING PINS
B - HEATER COIL
C - TRANSITE HEATER BLOCK
D - TUBING CUTOFF HEAD
E - MOVABLE HEAD
F - FRAME
G - 110 AC POWER LEADS
H - ADJUSTING WHEEL
I - SUPPORT TUBE
J - FORWARD HANDLE
SCALE - INCHES

FIG. 1. Plastic tube sealer and cutter

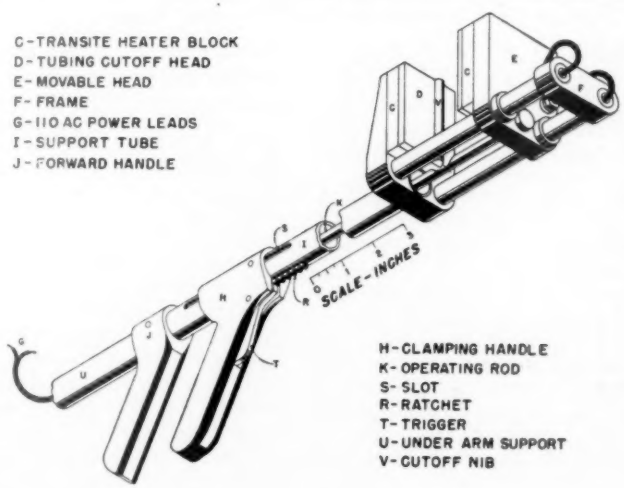

C - TRANSITE HEATER BLOCK
D - TUBING CUTOFF HEAD
E - MOVABLE HEAD
F - FRAME
G - 110 AC POWER LEADS
I - SUPPORT TUBE
J - FORWARD HANDLE
SCALE - INCHES
H - CLAMPING HANDLE
K - OPERATING ROD
S - SLOT
R - RATCHET
T - TRIGGER
U - UNDER ARM SUPPORT
V - CUTOFF NIB

FIG. 2. Proposed design

handle J to the frame F can be varied. In the unit described, this is 3 feet.

Structural Details

The heater blocks consist of 2 in. × 2 in. × ⅜ in. Transite slabs milled out to 1½ in. × 1½ in. × ¼ in. inside dimensions.

The heater wire separators are ⅜ in. × ⅛ in. dia. ceramic pegs cut from ceramic thermocouple wire sleeves, spaced on ¼ in. centers.

The resistance wire is Kanthal A wire,* B & S #30, resistance 8.362 ohms/ft. Each heater block contains 12 feet of this wire wound as a coil ⅛ in. OD × 6 in. long. Both heaters are parallel wired to a 110-volt source, and each develops 100 watts.

The cutoff head D with cutoff nib is presently mounted to the tube sealer as a slide-on attachment. One modification under way at present is to dovetail the cutoff nib V directly into the heater block face plate, as indicated in Fig. 2.

Figure 2 illustrates a proposed tube sealer embodying the same heater details as in the first design, but with modifications in heater movement to effect greater operational simplicity, speed, and facility.

In this design, the handle H is connected to the rod R through the slot S. The rod R is in turn fixed to head E so that drawing handles H and J together by a squeezing grip draws heads D and E together. Sealing pressure is maintained by ratchet R and released by pressing trigger T.

Note the dovetailed cutoff nib V. This cutoff nib can be replaced by a dovetailed insert which is flush with the heater block face when it is desired to seal without cutting.

Study of Animal Behavior with Radioisotopes†

Radioisotopes have recently been used to advantage in tracing the position and movements of whole animals. Harmless amounts of radioactive material when attached to animals permit many types of ecological and behavior studies to be carried out under natural conditions without the disturbing presence of a human observer.

One application of this principle involved homing experiments with wild birds in which the birds were captured at their nests, carried to a distance, and released. In most investigations of the homing ability of birds, it has been necessary for an observer to watch the nest of each bird throughout all of the daylight hours between its release and its return. In planning experiments of this type in the arctic, it was clear that the continuous daylight would intensify the difficulties of visual checking, and an automatic recording device which would register the time of return of an individual bird, as distinguished from its mate or others of the same species, was developed.

A minute amount of radioactive material was attached to the conventional aluminum bird band; and a recording radiation intensity meter was operated near the nest to measure very accurately the time of a tagged bird's return. When the tagged bird returned to its nest, a clear rise to a new level on the chart recorded this fact unequivocally. The instrument also continued to record the subsequent arrivals and departures of this bird.

* C. O. Jeliff Mfg. Co.

† From a paper by Donald R. Griffin, Dept. of Zoology, Cornell University, Ithaca, N. Y., presented at the Dec. 29th meeting of the American Association for the Advancement of Science in New York City.

Because of their range and penetrating power, gamma rays are usually the best for tracing animals. The important quantity to be considered is ordinarily the total dose of radiation delivered to any part of the animal during the entire life of the isotope. This total dose r, in roentgens, is given by

$$r = 0.035RT$$

where R is the initial radiation intensity in milliroentgens per hour, and T is half-life of the material in days.

The maximum permissible value of r used has been 1,000 roentgens, since this is the generally accepted value of the "threshold erythema dose" in human patients, that is, the dose of gamma rays which when administered *at one sitting* produces a just noticeable reddening of the skin 2 to 4 weeks after exposure in 80% of the cases. However, the same dose of gamma rays delivered over a longer period is known to be much less effective; and this is a substantial factor operating in our favor.

The closeness of contact between the animal and its radioactive tag is of primary importance, for, if the radioactive material touches or enters the animal's body, very high local concentrations and radiation intensities may occur. However, with gamma-ray emitters, this problem is easily solved by locating the active material in the center of a capsule of some light material such as aluminum which is resistant to breakage and corrosion. One then knows that unless the capsule is violently broken open the material never comes closer to any organism than the radius of the capsule. Aluminum will not appreciably absorb the gamma radiation which one wishes to detect at a distance, but it will in most cases provide helpful protection from beta radiation which otherwise would increase the dose received by the animal without assisting in the instrumental detection.

The principle of placing gamma-ray emitters at the center of such a capsule is a most useful one, both to increase the permissible dose and also to simplify the calculation of the radiation intensity actually reaching the tagged animal. One can consider the material at the center of the capsule to be a point source radiating uniformly in all directions, so that the intensity at the surface of the capsule will vary inversely as the square of its radius. At small values of the radius d, the inverse square relation may not hold exactly, but in these cases the increase in radiation intensity as one decreases d is less than predicted by the inverse square relation, so that in assuming this relation one errs on the conservative side.

The initial radioactivity of the material in microcuries, c, can be calculated by

$$c = \frac{rd^2}{0.035(\mathrm{IA})T}$$

where r is the maximum permissible dose in roentgens, d is the radius of the capsule in cm, IA is the radiation intensity produced at 1 cm from a point source, and T is the half-life in days.

Practicable Range

The practicable working range is limited not so much by the sensitivity of available detecting instruments as by the universal presence of natural background radiation, of roughly 0.006 mr/hr. The gamma rays from the tag must be definitely above this intensity level at the detecting instrument. The practicable working range is $\sqrt{(\mathrm{IA})c/0.020}$.

This may give incorrect values at very close ranges where the inverse square relation does not hold, but at such ranges detection is ordinarily not a problem. The range indicated is for air; but gamma rays are so penetrating that the animal's body or a few small

obstructions will not reduce the ease of detection to any appreciable extent. A special case would be the tracing of aquatic animals under water or burrowing animals beneath the surface of the ground. In such cases one can calculate the range and then determine how serious is the absorption in water or ground by taking into account its density.

In choosing materials for tagging animals the half-life T is obviously an important consideration, for when T is small the permissible amount of initial radioactivity is increased, together with the practicable range of detection. Furthermore it is always preferable in work of this sort to employ short-lived isotopes which automatically become harmless after a short period of time no matter where they may be carried. There are obvious difficulties in arranging delivery from the source before the short-lived material has decomposed. There are some short-lived isotopes available with initial values of the specific activity so high that adequate radioactivity will remain even after the passage of several half-lives.

The chief limitation of radioactive tagging is the short range at which even short-lived gamma emitters can be detected; the upper limit seems to be several feet. However, the working range and general usefulness of the method might eventually be enhanced by the use of *directional* detecting instruments, which have already been developed in several forms. A directional detector, if pointed towards the tag, would receive the same useful signal, but the background noise would be reduced, and there would undoubtedly be some over-all increase in working range. Such detectors would also have the advantage of showing the direction from which the radiation of the tag was arriving; hence they would be especially useful for locating tagged animals under water or ground. In such cases a non-directional detector can merely be moved about until a maximum intensity is indicated; and one then knows only that the animal is directly beneath that position. But a directional detector would permit a rough-and-ready process of triangulation for determining the animal's depth below the surface.

Freezing Point of Uranium Determined by NBS

Concurrent with the great increase of interest in the metal, uranium, brought about by the role of this metal in the field of atomic energy, there has been an initiation of investigations to obtain more accurate values of certain physical properties of the element. Previously, the metal was of little practical importance and was not available in a state of sufficient purity to give a positive significance to the results of determinations of many of its physical properties. Only a few of the physical constants of uranium were listed in tables published before 1943, and those listed were highly discordant.

Some recent work on the freezing point of uranium has been done at the National Bureau of Standards [Andrew I. Dahl, Harold E. Cleaves, *J. Research Natl. Bur. Stds.* **43,** 513 (1949)]. The data obtained indicate the following:

1. The freezing temperature of uranium of about 99.99% purity is 1,133° ± 2° C.

2. The freezing temperature was not greatly affected by the crucible material, similar values for the freezing temperature being obtained in beryllia, thoria, and graphite crucibles.

3. Holding the metal at temperatures just above the melting point for several hours resulted in a decrease in the content of several impurities, by volatilization and by migration to the top and side walls. This increase in the purity of the metal was accompanied by an increase in the freezing tempera-

ture to a final constant value, 5° or 6° C above the initial freezing temperature.

Radioisotopes Applied To Research Problems

With the increased availability and decreased cost of radioactive materials, there has been a step-up in the research being done with them. Joseph J. Pescatore, chief radiochemist of the U. S. Testing Co., Hoboken, N. J., reports work done on the following problems:

Causes of paint blisters. The probable cause of paint blisters was studied using the isotopic technique. Cobalt resinate was synthesized with cobalt-60. This compound was added to the vehicle of the paint. Test panels were prepared, dried, and then blisters were allowed to form using standard procedures. The paint blisters were peeled off and the panel surface checked for the presence of any radioactivity. In some cases no activity was present, indicating lack of adhesion between the paint and the panel surface. In other cases, radiation was detected on the panel surface, indicating lack of cohesion in the paint itself. Following such a procedure, a film thickness one molecule thick can be detected.

Adsorption of a dryer by the pigment. Another problem confronting the paint industry deals with the behavior of various activators which are added in paint formulations. For instance, a freshly prepared paint may have a drying time of three hours, whereas the same paint after considerable period will exhibit a much longer drying time—all other factors being constant. It was suspected that the pigment adsorbs some of the activator, preventing it from serving its purpose fully. The problem was answered satisfactorily using the isotopic means. An activator was selected and properly treated to render it radioactive. A known amount was added to the paint while stirring continuously. At definite intervals of time a weighed sample of paint was separated into its pigment and vehicle by centrifuging, a standard procedure. The pigment was dried and checked for the amount of radioactivity it emitted. With other data, the amount of activity was correlated to the percentage of activator that was adsorbed onto the pigment. Thereby, the rate at which this phenomenon took place was obtained.

Oxygen Presence Increases Gene Radiation Damage

The greater the amount of oxygen available at the time of exposure to radiation, the greater the radiation damage to genes, reported Dr. William K. Baker, assistant professor of zoology at the University of Tennessee and a consultant in the Biology Division of Oak Ridge National Laboratory, at the recent AAAS meeting in New York.

The tiny fruit flies, Drosophila melanogaster, were used as subjects. One group was exposed to X-rays in oxygen environment; the second, in a nitrogen environment. Within each group, exposures were made at 27° and 2° C. Drosophila specimens from both groups were exposed to standard X-ray doses varying from 1,000 to 5,000 r.

Following irradiation, flies from each sample were mated, 10,696 such matings taking place during the experiment. The findings are based upon observation of the resulting offspring. Specifically, the number of sex-linked lethal mutations—mutants which, in this case, killed the males inheriting radiation-damage genes—were counted.

The conclusion was reached that gene damage is dependent upon oxygen concentration and duration of exposure as well as upon intensity of the radiation itself. Temperature appears to be important only as it affects oxygen concentration. —END

BOOKS

The Pharmacology and Toxicology of Uranium Compounds (Div. VI, Vol. 1, of National Nuclear Energy Series), edited by Carl Voegtlin and Harold C. Hodge, McGraw-Hill Book Co., Inc., New York, 1949, Parts I and II, 1084 pages, $10. *Reviewed by William T. Salter, Professor of Pharmacology, Yale University School of Medicine.*

As part of the "National Nuclear Energy Series," a comprehensive survey of the toxicity chiefly of stable (nonradioactive) chemical compounds derived from uranium has appeared under the capable editorship of two pharmacologists, Carl Voegtlin and Harold C. Hodge.

The material, supplied by some two score investigators and specialists, is divided into two parts. Part I concerns the pharmacology and toxicology of uranium compounds. Part II, the minor portion of the work, reports observations on the toxic action of fluorine and hydrogen fluoride. There is no doubt that this work will be regarded as *the* definitive synopsis of uranium poisoning for many years to come.

To a medical biologist, the able historical foreword and introduction by Professor Hodge of the University of Rochester will be most helpful, supplemented by Joe W. Howland's studies on human exposure to uranium compounds. There is even a summary of simple biometrics in Chapter 3, by Tiedeman, Kogan and Wantman, which should interest most first-year graduate students in biology.

It is impossible to mention all of these contributions, but a few may be cited which appealed to this reviewer. The pathological anatomy of uranium poisoning is described by Barnett and Metcalf, and illustrated with some excellent colored photomicrographs demonstrating renal pathology. Wills has described the characteristics of uranium poisoning with special emphasis on the pathological physiology thereof. The toxic changes in skin and eye have been discussed by Arcutt, and the toxicity following inhalation by Stokinger and his associates. Dounce has expounded the action on enzymes and proteins as a key to the mechanism of uranium toxicity, with special emphasis on catalasuria as a sensitive test for uranium poisoning. In screening human subjects for tubular damage, this test should prove valuable to the health officer or industrial physician.

Stokinger's chapter on toxicity following the inhalation of fluorine and hydrogen fluoride is a valuable self-contained monograph, but has little relation to the rest of the work. It should be listed separately by librarians and indexers lest it be lost.

This work, all in all, is a splendid monument to the cooperative efforts of the University of Rochester and the Manhattan Project.

The two volumes should be available in all medical schools, institutes of pathology and toxicology, and laboratories connected with industrial hygiene.

Tables de Constantes et Données Numériques: Vol. 2, Constantes Sélectionnées, Physique Nucléaire, tabulated by R. Grégoire under the direction of Frédéric Joliot and Irène Curie, published by Hermann & Cie, Paris, 1948, 135 pages and 14 charts, $10.50 (distributed in U. S. by Stechert-Hafner, Inc., New York). *Reviewed by Harold Brown, Physics Dept., Columbia University.*

These tables of nuclear data bring together, along with the conventional isotope tables, a considerable amount of other information which the experimenter (and theoretician) should find a

great convenience. Thus this work represents a considerably more extensive compendium than, say, the Table of Isotopes of Seaborg and Perlman [*Revs. Mod. Phys.* **20,** 585 (1948)].

The data on isotopes are divided into two sections. One concerns half-lives of unstable and relative abundances of stable isotopes, along with methods of production. The other gives beta and gamma energies (and the range of the betas). The alpha emitters are treated in a separate section, along with their associated gamma-radiations.

In view of the rapidity with which additional information on nuclear spectra is being accumulated, it is not at all surprising that a table of such data should contain many obsolescent pieces of information within a few months of publication. In particular, this reviewer noticed (among the light elements) such entries for N^{13}, A^{41}, O^{19}, and Al^{28}, reflecting the fact that the data included were all obtained before 1947. In most cases only one set of results is given, but sometimes conflicting results are presented.

One advantageous feature is the inclusion of an unusually complete list of methods of production of the artificial radioelements, and half-thicknesses for absorption in gm/cm² for β-emitters.

The Q values for about two hundred nuclear reactions of all kinds are presented in a separate table, which is followed by a selected list of sets of ions whose mass differences have been accurately measured by mass-spectrographic methods. A very useful and convenient section contains the masses in atomic mass units (on the physical scale), the packing fractions, and the binding energies (in both millimass units and Mev) for all stable and some radionuclei.

Under the title "Characteristics of Stable Atoms," information is included on the spins, magnetic moments, gyromagnetic ratios, and quadrupole moments of these nuclei.

This reviewer finds particularly interesting a list of cross sections for various transmutations at selected energies; this includes (d,n), (d,p), (γ,n) and (n,α) reactions, among others. A much more extensive table of this type (or better still, a set of graphs such as now exists for neutron reactions) would provide a great deal of desirable information with which one could predict the importance of competing reactions as a function of particle energy.

A number of range-energy curves are given. These include a set for protons in air (energies up to the somewhat arbitrary limit of 175 Mev), electrons in air and aluminum (up to 3 Mev), and gammas in Al, Cu, and Pb from 10 kev up to 25 Mev. A colorful isotope chart concludes the volume.

Not only are nuclear physics data of standard types being gathered with increasing rapidity, but new kinds of information (as, for example, in the high-energy region) are becoming important. In these circumstances, it seems highly unlikely that any *definitive* compilation of all the desirable information will be issued in the foreseeable future. In the meantime, the only possible procedure is to have on the reference shelf a large number of overlapping summaries, all at least somewhat dated. This volume fills a useful place on that shelf.

(NOTE: For information on the availability of Vol. 1 of these tables, see below.)

BOOKS RECEIVED

Tables de Constantes et Données Numériques: Vol. 1, Constantes Sélectionnées, Longeurs D'Onde des Emission X et des Discontinuités D'Absorption X, by Y. Cauchois and H. Hulubei, published by Hermann & Cie, Paris, 1947, 200 pages and 4 charts, $7 (distributed in U. S. by Stechert-Hafner, Inc., New York). *(See review of Vol. 2 of these tables in the preceding columns.)*

NUCLEONIC EVENTS

PIKE NAMED ACTING HEAD, STRAUSS RESIGNS FROM AEC

President Truman recently designated Sumner T. Pike to serve as acting chairman of the Atomic Energy Commission, pending appointment of a successor to David E. Lilienthal, who left office on February 15.

The resignation of Lewis L. Strauss was also made known recently. The fourth to resign from the original five-man commission as set up in 1946, he plans to leave April 15.

After that date, only three members will remain on the Commission. They are Gordon E. Dean, Henry D. Smyth, and Pike, who is the last of the original commissioners and will, it is said, leave the AEC on June 30 when his term of office expires.

ISOTOPE OF ATOMIC NO. 97 DISCOVERED AT BERKELEY

Good evidence has been obtained for the identification of an isotope of the new artificially made chemical element with atomic number 97, bringing the total number of known elements to 97, according to an announcement made by the Radiation Laboratory and Department of Chemistry, University of California.

This newest of the synthetic elements was prepared by bombarding a minute amount of americium, another synthetic element, in the Crocker Laboratory 60-inch cyclotron. The successful experiments which resulted in the identification of element 97 climaxed four years of work on the problem in which the necessary new chemical and nuclear data were accumulated. It was necessary to predict accurately the chemistry of the new element since it had to be separated rigorously from intensely radioactive americium and reaction products before its own radioactivity could be detected. It was also necessary to anticipate the radioactive decay properties of the particular isotope produced in order to know what to look for, how long to bombard the americium and how much time could be employed for the chemistry.

The identification of element 97 was made by Dr. Stanley G. Thompson and Mr. Albert Ghiorso, research associates, and Dr. Glenn T. Seaborg, professor of chemistry, all of the Radiation Laboratory and the Department of Chemistry.

The scientists suggest as the name for the new element, berkelium (pronounced berk'-li-um), having the chemical symbol Bk, in honor of the city of Berkeley where the discovery was made.

Berkelium has as its principal oxidation state in aqueous solution, +3, but can also be oxidized to +4 as would be predicted according to the actinide theory for heavy element structure (NU, Nov. '49, p. 16). The berkelium was isolated by combination of precipitation reactions and separations on ion exchange resin columns making use of the two oxidation states.

The particular isotope prepared is thought to be Bk^{244} or possibly Bk^{243} and decays principally by electron capture. However, it has appreciable alpha-branching (0.1%) and is distinctive in that it has three well-defined alpha groups. The half-life is only 4.8 hours so that all of the difficult chemistry must be accomplished rapidly.

PUBLIC HEALTH SETS UP HEALTH PHYSICS BRANCH

Formation of a new unit under the Public Health Service, Federal Security Agency, to develop a radiological health program to meet potential health hazards created by increased use of radioactive materials and radiation-producing machinery was announced recently by Acting Federal Security Administrator John L. Thurston.

This radiological health branch under the direction of E. G. Williams, will develop a training program in radiological health for PHS officers and other public health workers, and act as a source of information on radiological health for other PHS units, for other Federal agencies, and for State and local health agencies.

INSURANCE ENGINEERS STUDY HEALTH PHYSICS

About 100 insurance engineers from coast to coast representing about 39 casualty companies attended a five-day session on "Insurance Aspects of Health Physics," from Feb. 6–10, at Brookhaven National Laboratory.

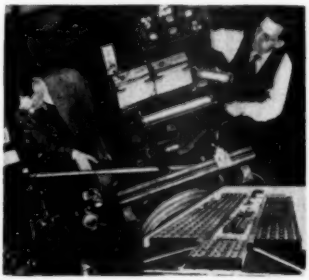
The course, arranged and directed by Brookhaven's Health Physics Division, provided advanced and detailed information on health problems involved in distribution and use of radioisotopes. Cooperating units were AEC'S Division of Biology and Medicine and Isotopes Division, Brookhaven National Laboratory, New York Operations Office and the Joint Casualty Committee on Radiation, representing the casualty insurance companies.

AEC SPONSORS RADIOLOGICAL MONITORING TRAINING COURSES

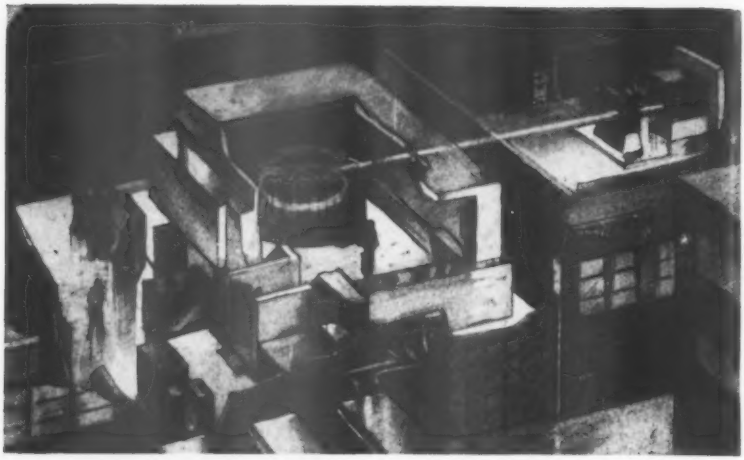
The Atomic Energy Commission, in cooperation with the National Security Resources Board and the General Services Administration, will sponsor three five-week instructor training courses in radiological monitoring techniques for qualified educators and technicians selected by State governors.

Two of the three radiological monitoring courses will be offered, beginning March 13, at the Brookhaven National Laboratory, Upton, L. I., and the Atomic Energy Project, University of California at Los Angeles, Calif. The third will be offered, beginning April 3, at Oak Ridge, Tenn. The Oak

ABOUT THE COVER



YESTERDAY'S mass spectrometer and today's gaseous diffusion plant are combined in this month's cover picture to commemorate the ten-year anniversary of the first separation of fissionable U^{235} from natural uranium. Kenneth H. Kingdon and H. C. Pollock of the General Electric Research Laboratory, shown at their Nier-type spectrometer in the decade-old photograph, were one of the first research teams to complete the separation. Dr. Kingdon is shown making a power-supply adjustment as Dr. Pollock pours liquid air into the cold trap of a vacuum pump. The simplicity of their equipment is contrasted to that contained under the 60-acre roof of the K-25 plant at Oak Ridge shown in the inset. Gaseous diffusion there today accomplishes U^{235} separation in the largest continuous process plant in the world. Photos from General Electric Co. and Atomic Energy Commission.



The 300,000,000-volt synchrotron at Massachusetts Institute of Technology recently passed its first operating tests. In the drawing above, the 12-foot diameter synchrotron appears in the center. The control room is on the left; in the foreground are banks of capacitors, a portion of which are shown in the photograph at the left. Pulses of electrons from a betatron-type accelerator are pushed to higher energies as they pass an acceleration gap across which a high-frequency alternating voltage, derived from the capacitor banks, is applied. After acceleration through 250,000 turns around the tunnel-like path in the 24 wedge-shaped magnet sections of the synchrotron, the electrons are deflected through a slit in the shielding and enter the experimental apparatus shown in the upper right-hand corner of the sketch.

Ridge course will be administered jointly by the Oak Ridge Institute of Nuclear Studies and the Oak Ridge National Laboratory.

GE TO GIVE TRAINING COURSES AT HANFORD WORKS

Electrical and chemical engineers, physicists and metallurgists are being recruited for a rotational training course at General Electric's Hanford Works at Richland, Wash. The first to be set up by an atomic-industry plant, the course will accept only recent graduates.

The course will give a "substantial number" of recruits from 9 to 18 months training in many parts of the plutonium manufacturing plant at Hanford. "Compartmental" security enforced in the early stages of manufacture at the plant prevented most technicians from becoming acquainted with any operation outside their particular units.

Technical work offered in the training

course, expected to start in February, can be applied for graduate or undergraduate credit at four western schools, the Universities of Oregon, Idaho, Washington and Washington State.

Dr. Winton I. Patnode, assistant to the general manager of the GE Nucleonics Department at Hanford, is currently recruiting from colleges west of the Mississippi. Eastern colleges will be visited this spring.

AEC INSTRUMENTS BRANCH SHIFTED TO WASHINGTON

The Radiation Instruments Branch of the AEC's Division of Production has been transferred from Oak Ridge to Washington, D. C. Robert L. Butenhoff is acting chief of the branch.

This group coordinates instrument activities within the AEC. The branch compiles, edits and publishes several different types of instrumentation publications for internal AEC use, in addition to a radiation instruments catalog, available to the public.

NEW ZEALAND LEGISLATURE ACTS ON RADIOACTIVE SUBSTANCES

A Radioactive Substances Act will shortly go into effect in New Zealand. The bill, recently passed, is modeled on similar legislation passed in England in 1948.

The act empowers the Minister of Health, acting on the recommendations of the Radiological Advisory Council, to determine whether a person is qualified to use radioactive substances or X-rays in medical treatment.

The manufacture, purchase, distribution, importation, exportation and use of radioactive substances will be permitted only subject to a government license. Scientific workers using isotopes, even in government laboratories, will therefore be compelled to procure a license. Likewise, a license will be required for the purchase and use of X-ray and other specified radiating apparatus.

U. OF TEXAS STARTS NUCLEAR RESEARCH PROGRAM

A new research program in nuclear and atomic physics was initiated at the University of Texas last month. Centered around a $45,000 5-Mev Van de Graaff generator, the program is directed by Emmett L. Hudspeth, formerly of the Bartol Research Foundation, Swarthmore, Pa.

IN BRIEF

➤Secrecy being enforced on all atomic projects is inefficient, extremely costly and hinders progress in research, according to Dr. I. I. Rabi of Columbia University.

➤*A maximum flux of thermal neutrons of* 5.7×10^{13} *per sq cm per second has been reached in the Canadian pile at Chalk River. While, for technical reasons, it has not yet been possible to maintain this flux continuously, it is expected that the new level will be regained and even surpassed in the near future.*

➤W. J. Bennett, president of Canadian-owned Eldorado Mining and Refining Co., reports progress in development of an airborne detector for radioactive minerals for possible use in uranium prospecting.

➤*The* $10,000 *bonus offered by the AEC for the discovery of rich deposits of uranium ore is virtually impossible to win, according to Charles H. Dunning, director of the Arizona Department of Mineral Resources, because of the strictness of requirements on grade and type of ore.*

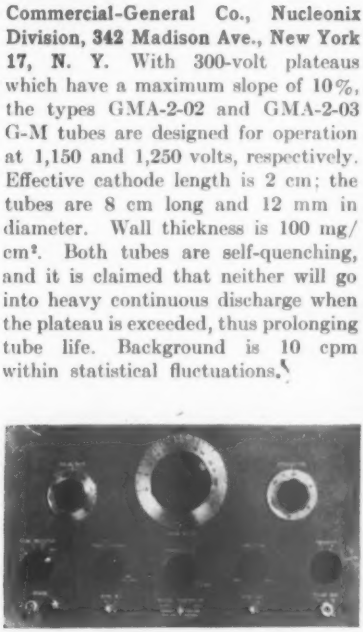
➤"Secrecy suppresses basic physical knowledge concerning the universe which should be used to stimulate physical thinking everywhere," says Dr. Samuel K. Allison, director of the Institute of Nuclear Studies at the University of Chicago. "The existence of an inner core of secret facts vitiates

(Continued on page 82)

PRODUCTS and MATERIALS

MIDGET G-M TUBES

Commercial-General Co., Nucleonix Division, 342 Madison Ave., New York 17, N. Y. With 300-volt plateaus which have a maximum slope of 10%, the types GMA-2-02 and GMA-2-03 G-M tubes are designed for operation at 1,150 and 1,250 volts, respectively. Effective cathode length is 2 cm; the tubes are 8 cm long and 12 mm in diameter. Wall thickness is 100 mg/cm². Both tubes are self-quenching, and it is claimed that neither will go into heavy continuous discharge when the plateau is exceeded, thus prolonging tube life. Background is 10 cpm within statistical fluctuations.



PULSE GENERATOR

Hewlett-Packard Co., 395 Page Mill Rd., Palo Alto, Calif. The model 212A pulse generator has a repetition rate which is continuously variable from 50 to 5,000 pulses per second. Pulse rate can be controlled internally or from an external synchronizing source; synchronization pulses are available either in advance or following the main pulse. The 50-watt pulse which the instrument is said to deliver has a rise and decay time of 0.02 μsec. Pulse length is continuously variable from 0.07 to 10 μsec. Because of the low internal impedance of 50 ohms or less, it is claimed that pulse shape is virtually independent of load. Both positive and negative pulses may be generated.

GAMMA SURVEY METER

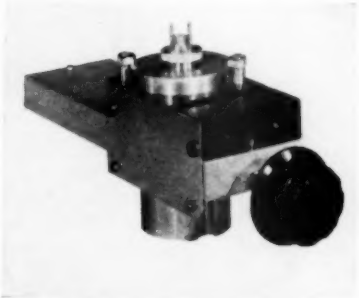
General Electric Co., Special Products Division, Schenectady 5, N. Y. The "long-probe gamma survey meter" is designed for monitoring and survey work. Scintillations caused by gamma radiation striking a phosphor at the end of a four-foot probe are detected by a photomultiplier tube. A small electronic tube amplifier couples the photomultiplier tube to a microammeter which is calibrated in roentgens per hour. Power for operation is supplied from batteries and a plug-in high-voltage regulated supply in a separate case equipped with a shoulder strap.

SURVEY METER

Tracerlab, Inc., 130 High St., Boston 10, Mass. With its meter calibrated in both mr/hr and cpm, the model SU-5 beta-gamma survey instrument provides full-scale ranges of 0.02, 0.2, 2.0, and 20 mr/hr, with corresponding cpm scales of 100, 1,000, 10,000, and 100,000. The TGC-5 30 mg/cm² glass-wall Geiger tube is enclosed in a removable probe shield with a 1,300 mg/cm² wall. Gamma radiation can be measured in the presence of beta radiation with maximum energy of 2.5 Mev. With the probe shield removed, the Geiger tube is protected by a metal cage with 53% open area. Beta rays with energies as low as 0.3 Mev can be measured.

VACUUM MEASUREMENT

Distillation Products Industries, Ridge Road West, Rochester 3, N. Y. The DPA-38 ionization gage control circuit, designed for use with the VG-1A ionization gage tube, provides direct reading of vacuum measurements. The smallest scale division is 2×10^{-9} mm of mercury. Negative exponent of the number of millimeters is read from the range selector, and the coefficient is read on the dial gage. A heavy-duty, adjustable, automatic relay is said to assure maximum life of the ionization tube. The circuit operates from a 110-volt, 60-cycle line.



GOOCH-TYPE COUNTERS

Nuclear Measurements Corp., 3339 Central Ave., Indianapolis 5, Ind. Two types of Gooch crucible proportional counters, interchangeable with the flat sample counters used with the PC-1 counter, are now available. The GCC-1 uses a 15 ml crucible; the GCC-2 uses either a 15 ml or a 30 ml crucible. Both models of the crucible are windowless. Beta background is about 5 cpm; with a counting rate of 500,000 cpm claimed for use with the PC-1, a resolution loss of 1% per 100,000 cpm is possible. The gas used is a mixture of 90% commercial argon and 10% CP-grade methane.

ELECTRONIC RELAY

Servo-Tek Products Co., 4 Godwin Ave., Paterson, N. J. Extreme sensitivity is claimed for a new electronic relay system which may be mounted on a standard four-inch electrical con-

nection box. Operating from a 115-volt 60-cycle line, the unit uses no filament to draw standby power. Unit operation is initiated by the contact of a drop wire, contact-making instrument, or any conductive medium between the two contacts having a resistance as high as one million ohms. Maximum current flow through the initiating resistance is in the order of microamperes.

BETA-GAMMA MONITOR

Nuclear Instrument and Chemical Corp., 223 W. Erie St., Chicago, Ill. Utilizing the same circuit as its predecessor, the model 2610A portable count-rate meter detects both beta and gamma radiation. The plug-in type Geiger tube is covered with a sliding beta shield. A meter calibrated in mr/hr and cpm is used to show counting rate; calibration may be checked against an attached radioactive source. Earphones are provided for aural monitoring.

PROSPECTING COUNTER

Precision Radiation Instruments, Inc., 5478 Wilshire Blvd., Los Angeles 36, Calif. The model 106 Geiger counter, designed for field use, weighs 3½ lbs. Sensitive to both beta and gamma radiation, it is said to detect 160 kev betas. Ranges of 20, 2, and 0.2 mr/hr are provided on the meter by switching. Earphones and a neon flasher also provide indications of counting rate. Battery operated, the counter uses a 900-volt G-M tube with a 30 mg/cm² window. High voltage is regulated by an electronic circuit.

R-F SHIELDING

Ace Engineering & Machine Co., 3642 N. Lawrence St., Philadelphia 40, Pa. Designed for a minimum of 100-db attenuation from 0.15 to 1,000 megacycles in fields as low as 1-μvolt/meter, a portable r-f shielded room uses double copper-mesh screening. Sections are designed so that the size of the shielded room may be changed. Provision is made for including a latched door and service entries.

NUCLEAR TRACK EMULSIONS

Eastman Kodak Co., Rochester 4, N. Y. An intermediate-speed photographic emulsion for recording nuclear tracks, type NTB2, is said to be sensitive to 400-kv electrons. A second emulsion type NTC3, is designed to record low-energy alphas and protons to 7 Mev.

LITERATURE AVAILABLE

Chronotest Millisecond Timer. Describes electronic timing instrument which measures millisecond intervals with a one to two percent accuracy. *Bulletin* 1030, *Herman H. Sticht Co., Inc., 27 Park Place, New York 7, N. Y.*

Ruggedized Instruments. Construction of electrical meters which have been designed to withstand shock is outlined. *Marion Electrical Instrument Co., Manchester, N. H.*

Bulletin 1810A. Describes Titrilog for recording traces of sulfur compounds. *Consolidated Engineering Corp., 620 N. Lake Ave., Pasadena 4, Calif.*

NEW ECONOMY MODEL COUNTING RATE METER

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whole areas of scientific inquiry and technological development extending far from the actually classified data. No one can remember from day to day just what is classified, and to be safe, avoids discussing whole fields of research and technology."

NUCLEAR NEWSMAKERS

William Webster, executive vice president of the New England Electric System, has been nominated to be chairman of the Research and Development Board. In addition to having been first chairman of the Military Liaison Committee of the AEC, he was director and chairman of the Atomic Energy Committee of the New England Council.

V. Lawrence Parsegian, former Director of Physical Research for the Kellex Corp., has been named director of the Division of Technical Advisers, New York Operations Office of the AEC. Dr. Parsegian will be responsible for the administration of AEC basic research and development contracts in the physical sciences with more than fifty academic and industrial research institutions in the Northeast. He will also serve as chief adviser to the New York Operations Office on technical matters involved in the AEC's uranium feed and reactor materials program.

John McElhinney, nuclear physicist from Los Alamos Scientific Laboratory, has joined the staff of the Radiation Physics Laboratory of the National Bureau of Standards. He will work on nuclear reactions and high-energy X-rays.

An engineering advisory committee has been appointed to assist the Idaho Operations Office of the AEC on the planning and development of the Reactor Testing Station. The members are: **Gen. L. J. Sverdrup,** chairman; **H. M. Crothers;** and **W. W. Horner.**

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